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A LAYMAN'S LOOK AT ORBITAL DEBRIS

by

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Artificial space debris is a new and threatening reality. This thesis examines the requirement of acknowledging this threat as one of the major considerations in the design of Low Earth Orbit (LEO) satellites. The paper commences with a comprehensive view of the issue; the facts of the case are presented. It is necessary to understand the physical fundamentals of this multi-faceted problem in order to view it as a genuine threat to satellites. Following this introduction, an overview of how the problem is currently approached, from a political and technical standpoint, is discussed. Strategies for coping with the space debris issue are then presented. From these, the paper focuses on the most promising prospect for the future. It highlights the need for new and responsible satellite design philosophies in order to deal with the uncertainties of the LEO environment. The research effort concludes that space debris considerations must be incorporated at the earliest phases of a satellite's design efforts and must be a continuing commitment throughout the operational life of a satellite.

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A LAYMAN'S LOOK AT ORBITAL DEBRIS

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Submitted in partial fulfillment
of the requirements for the degree of

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ABSTRACT

Artificial space debris is a new and threatening reality. This thesis examines the requirement of acknowledging this threat as one of the major considerations in the design of Low Earth Orbit (LEO) satellites. The paper commences with a comprehensive view of the issue; the facts of the case are presented. It is necessary to understand the physical fundamentals of this multi-faceted problem in order to view it as a genuine threat to satellites. Following this introduction, an overview of how the problem is currently approached, from a political and technical standpoint, is discussed. Strategies for coping with the space debris issue are then presented. From these, the paper focuses on the most promising prospect for the future. It highlights the need for new and responsible satellite design philosophies in order to deal with the uncertainties of the LEO environment. The research effort concludes that space debris considerations must be incorporated at the earliest phases of a satellite's design efforts, and must be a continuing commitment throughout the operational life of a satellite.

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I. INTRODUCTION

When speaking of space, one tends to associate it with terms such as "infinite" and "empty". For the most part valid, this description could not be farther from the truth in the context of near Earth space. Figure 1 is a graphical depiction of all catalogued items currently occupying near Earth space.

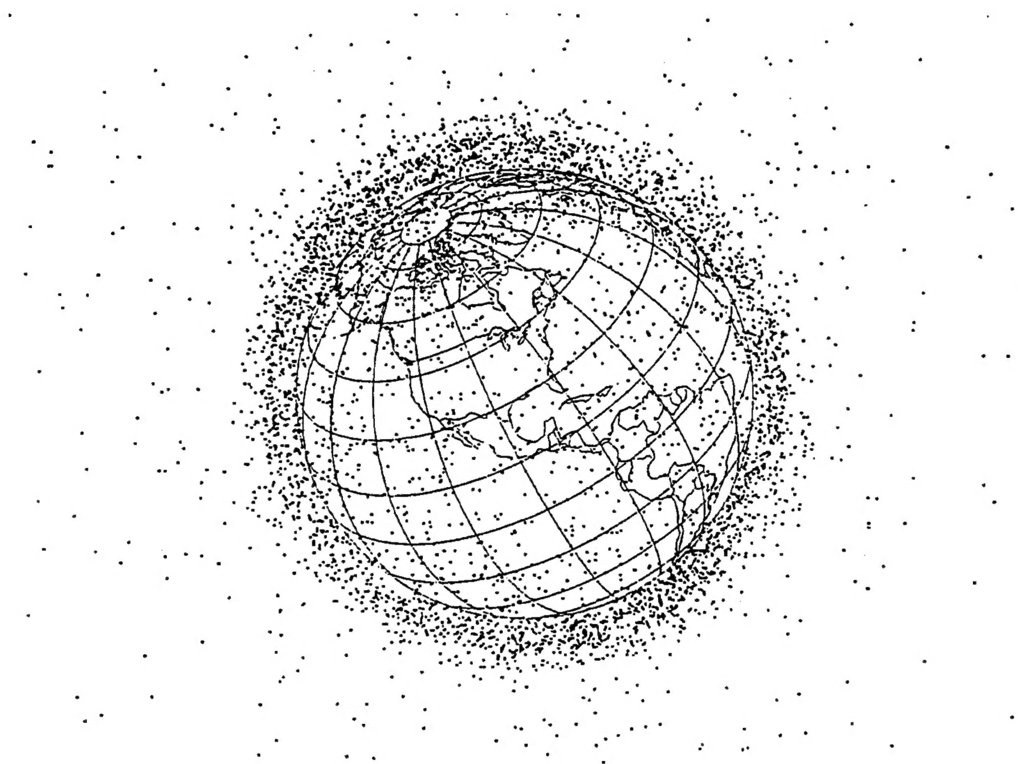


Figure 1. Graphical Depiction of Current Cataloged Space Objects. [Ref. 1, p. 7]

In 1957, the first artificial satellite was launched by the Soviet Union. Since then, space activities have continued, with the result that a large number of man-made objects remain in orbit about the Earth. Unfortunately, most of these objects no longer serve any

useful purpose. In fact, most of the objects are not spacecraft as such, but pieces resulting from breakups or otherwise associated with past launch operations. Collectively, these objects have been labeled "space debris."

There is a growing sense of awareness about the dangers these objects pose to both the present and future operations in space, spurred on by increased international participation. Technical research and open exchange of available information has allowed scientists new insight into the subject. Through these efforts, an inescapable fact has emerged: if appropriate measures are not applied, space debris will jeopardize nearly all future space activities.

A first step toward dealing with this problem is to learn to treat it as a genuine threat. The issue of space debris must be viewed as a serious space environmental problem. Unfortunately, the seriousness of the problem is often downplayed because of the previously mentioned misconceptions about space. As ESA stated in the preface to its report on space debris: "The sheer immensity of space is the main obstacle to the recognition of the issue of space debris." [Ref. 2, p. 3] The old adage "big sky, small plane" prevails, blinding the vast majority to the truth.

The eventual solution to the problem lies in changing these false perceptions and convincing decision makers that some manner of debris mitigation must be applied. This in itself will be a challenge, given that most mitigation measures are more expensive than present practices/applications and promise only a small, short term gain.

Part of the intent of this research effort is to help foster an increased sense of urgency in dealing with the space debris issue. Under current practices, the problem only worsens with time; it must be dealt with as a legitimate threat and with realistic solutions. The primary focus of this paper, however, is to examine the debris issue by coming to an understanding of the physical characteristics of debris, studying current related policies and practices, and evaluating conventional strategies for addressing the debris predicament. One possible venue for addressing the problem is also discussed. In general, it proposes that the incorporation of debris mitigation measures are vital to

addressing the space debris problem. Specifically, it notes that failure to implement these measures at the conceptual phase of spacecraft mission and operations design will result in both the potential loss of said spacecraft and the continued exacerbation of the problem. In order to support this endeavor, chapters within this paper have been designed to lead a reader to this established goal. Chapter II provides a comprehensive view into the basic fundamentals of the issue and gives a quantitative look at the space debris situation; it is intended to present objective, numerical data surrounding the issue. More importantly, however, it serves to educate the reader as to the true extent of the matter without having to revert to unsubstantiated cries of rhetoric. In this manner, inexpert readers can understand the limits of the problem; an informed reader can then make an informed decision concerning the predicament. The purpose of Chapter III is to illustrate the seriousness of the issue by demonstrating the degree of ongoing political and scientific efforts. It also serves to give the reader a feeling as to where the international space community currently stands on the subject of space debris. Chapter IV discusses conventional strategies and methods for coping with the current and projected debris environment. The core of the thesis, Chapter V, focuses on how to assure survivability in the space debris environment. The goal of this section is to show the reader that well thought-out actions are necessary in order to survive in LEO. Among other things, this proposal includes changing one's perspective as to how to approach the problem, coupled with new, trend-setting methodologies for spacecraft design and operational procedures.

II. ORBITAL DEBRIS: A NEW REALITY

The intent of this chapter is to provide a broad oversight into the fundamental properties and issues governing the space debris problem. It's purpose is to educate the reader on the major concerns in a cursory manner. This chapter has been intentionally written to present individual debris characteristics one at a time, without referring to or describing other closely related debris properties. As the reader will soon discover, this is difficult given the fact that so much concerning space debris is dynamic in nature and fundamentally a cause and effect relationship; that is, it's hard to talk about one thing without talking about another.

A. ORBITAL DEBRIS

Throughout this research, two distinct groups, at opposite ends of the debate, have come to light. The conservative group, for the most part, maintains that the problem is not that threatening and is far removed from our daily concerns. On the other hand, alarmists overstate the problem, and attribute inconsistencies in data to an automatic, worst case scenario. They tend to lose credibility in this manner. It is the intent of this chapter to provide factual information regarding the space debris issue.

People base their opinions on available information. There are many unknowns regarding the specific orbital debris population, distribution, and composition. We tend to speak of space debris in general terms. Causes for this degree of uncertainty are addressed later in this paper. For now, it is sufficient to note this lack of specificity, and keep in mind that it is an incomplete picture of the true orbital debris situation. Hence, whatever is known about the orbital debris environment paints either an accurate, best, or worst case scenario.

1. Definition

Up to now, this paper has made inappropriate use of the term 'space debris'. One could likely think that the term refers to any object orbiting the Earth. Actually, the term is quite specific. Space debris, also known as orbital or artificial debris, can be defined as those man-made objects in orbit about the Earth which are not considered to be active, useful satellite payloads. Incidently, these three terms will be used interchangeably throughout the remainder of this paper. Man-made orbital debris differs from natural meteoroids in two major respects: first, it remains captured in Earth orbit for the duration of its lifetime, and; second, unlike meteoroids, it is not transient through the space around the Earth. [Ref. 3, p. 1] Moreover, the meteoroid environment encompasses only particles of natural origin. This study considers only the artificial orbital debris environment.

a. Background

In general, the motion of an object in orbit is in the shape of an ellipse. For that matter, the orbits of all the planets in the solar system, as well as the orbits of all Earth satellites, are ellipses. In this context, orbital debris can be regarded as an Earth bound satellite. Since an ellipse is a closed curve, an object in an elliptical orbit travels the same path over and over. The time for the satellite to go once around its orbit is called the period. The degree of eccentricity of an orbit helps define the relative shape of the ellipse. Eccentricity values range from zero to one: a circle has an eccentricity of zero; as it approaches the value of one, the shape becomes more elliptical. With space debris, we concern ourselves with one of two types of orbits: low eccentric or pseudo-circular orbits, and eccentric or elliptical orbits. Circular orbits are special cases of elliptical orbits; they maintain a low eccentricity value and only approximate true circles. Objects in this type of orbit remain at a near constant altitude from the center of the Earth. Additionally, an object in this orbit maintains a nearly constant velocity value throughout its entire revolution. On the other hand, an object in an elliptical orbit varies in distance from the center of the Earth as it orbits. The closest point of approach to the

Earth is called the object's perigee; the object's maximum velocity occurs at perigee. The object's farthest point from the Earth is called the apogee; minimum velocity occurs at apogee.

The space around Earth is generally divided into three orbital regimes. The first is known as Low Earth Orbit (LEO). It is defined as an orbit with an altitude ranging anywhere between 150 to 5500 kilometers (km). The period of these orbits are on the order of 90 to 225 minutes; anywhere from 6 to 16 revolutions per day. Next, there is Medium Earth Orbit (MEO). It is defined by objects orbiting the Earth between LEO and Geosynchronous Earth Orbit (GEO). Lastly, as one might have guessed, there is GEO. The GEO orbit contains objects orbiting the Earth at an altitude of approximately 36,000 km. At this altitude, periodicity equates to approximately 24 hours. Active satellites normally occupy LEO and GEO. [Ref. 3, p. 2]

b. Types

For the purposes of this study, space debris is categorized into three general groups: sizes 0.01 centimeter (cm) and below, which can cause surface erosion on a spacecraft; sizes ranging between 0.01 cm to 1 cm, that can produce significant damage upon impact; and sizes larger than 1 cm, which can produce catastrophic damage upon impact.

2. Properties

a. Composition

Space debris composition is varied and includes dissimilar materials. This is because composition is directly related to the originating source of the debris. In turn, this peculiarity is due to the many different available sources of space debris. It is, therefore, difficult to categorize large space debris objects by composition. Sources of orbital debris will be discussed in more detail later

There is more certainty, however, when describing the composition of very small debris particles. Very small orbital debris particles are created by the disintegration

of spacecraft surfaces, such as paint flaking, plastic and metal erosion, and by firing of solid propellant motors, which produce aluminum oxide particles. New studies of impacts on returned spacecraft indicate that at sizes below 0.05 cm, space debris such as paint flakes or aluminum oxide pieces from rocket fuel comprise more than half the impacts. [Ref. 2, p. 190] Information gathered from the Long Duration Exposure Facility (LDEF) provides a more precise evaluation. A total of 1225 craters were detected on the gold and aluminum surfaces of LDEF; they were examined in order to determine the make-up of the projectile residues. From their findings, four subclasses of orbital debris were established: Fe-Ni-Cr rich particles representing stainless steel; Zn-Ti-Cl rich residues representing thermal protective spacecraft paints; Ag, Cu or Pb-Sn rich residues originating from solar cell or other electrical and electronic components of spacecraft; and pure aluminum. [Ref. 2, p. 190].

b. Velocities

Ideally, orbital debris will remain in its orbit as long as its velocity is sufficient to produce the required centrifugal force to counteract the pull of Earth's gravity. An object will remain in its orbit, traveling with the same overall velocity (for highly elliptical orbits, the velocity vector quantity remains constant; its component unit vectors vary in value), as long as these forces are balanced. In general, space debris objects pass one another at an average relative velocity of 10 km/sec. Relative velocity depends on the reference frame from which a velocity is measured. In the context of this paper, only velocities relative to a spacecraft should be considered. Tremendous relative velocities are generated whenever two orbiting objects approach and pass one another. Figure 2 shows the range of relative velocities for various altitudes and orbital inclinations. For instance, objects in LEO travel at an average velocity of 7 Km/sec; velocities in GEO are lower. A maximum relative velocity occurs when an object is at perigee in an elliptical retrograde orbit; minimum velocity will occur at apogee. Velocity is an important characteristic since space debris damage is a function of relative velocity.

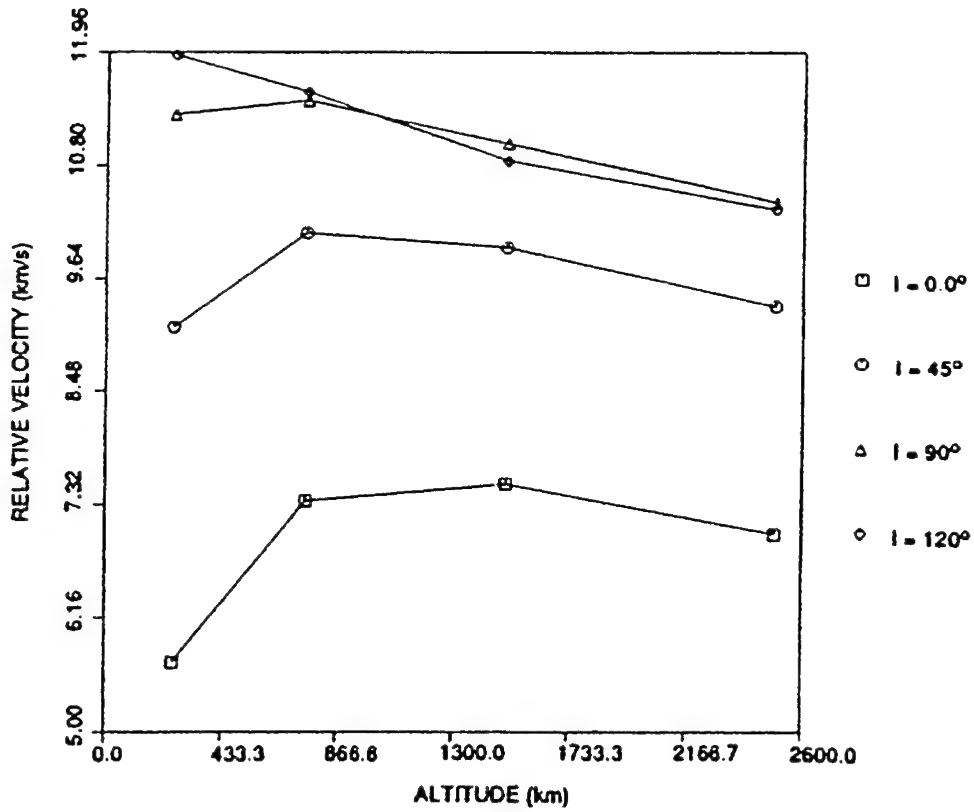


Figure 2. Average Relative Velocities for Different Inclination Settings. [Ref. 1, p. 72]

c. Mass

The greatest number of tracked objects are in LEO, the second largest number are in GEO, and the remaining objects are in MEO. The estimated mass of man-made orbiting objects within 2,000 km of the Earth's surface is about 3,000,000 kilograms (kg). This is 15,000 times more than the natural meteoroid mass. Most of this mass is contained in about 3,000 spent rocket stages, inactive satellites, and a few active satellites. A smaller amount of mass, about 40,000 kg, is in the remaining 4,000 objects currently being tracked by the US Space Command (USSPACECOM) radar [Ref. 3, p. 4]. Figure 3 depicts a pie chart diagram of the breakdown of cataloged object mass. Interestingly, LEO objects must be larger than about 10 cm in order to be maintained in

this catalog [Ref. 2,p. 252]. USSPACECOM and the catalog will be discussed at length in later chapters.

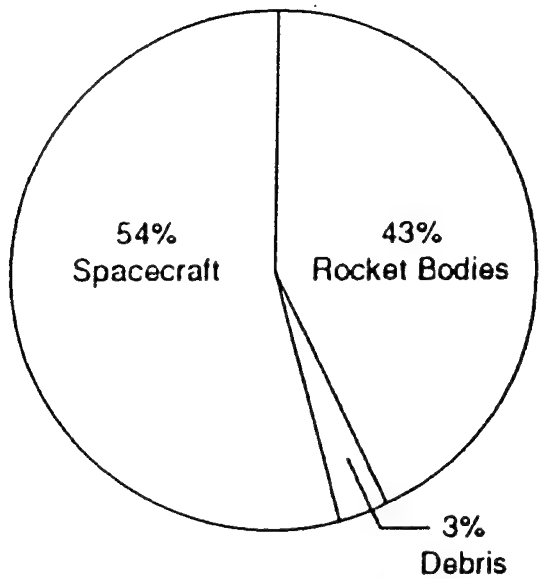


Figure 3. Mass Breakdown of Catalogued Objects. [Ref. 4, p. 478]

Given the variation in mass and velocities, space debris can create tremendous amounts of energy upon impacting with one another. In classical mechanics, the momentum of a particle is equal to its mass (m) times its velocity (v); its kinetic energy is equal to $\frac{1}{2}mv^2$. The effects of representative sizes of debris are shown in Figure 4.

d. Orbit

Most space debris objects are in a high inclination orbit. The inclination is the angle between the plane of the orbit (the elliptical plane) and the equatorial plane of the Earth. For operational, spent or intact rocket bodies, and inactive payloads, the originating launch site latitude and launch azimuth affect the orbit inclination. Nonetheless, space debris can occupy a large range of inclination planes. The range of objects in orbit by inclination is shown in Figure 5. Higher inclination objects will

produce larger relative velocities for low inclination satellites; most US space assets are in low inclination orbits. [Ref. 6, p. 85] The USSPACECOM data base has measured trackable objects with inclinations ranging from 0 through 145 degrees. Refer to Table 1 for a complete breakdown [Ref. 7, p. 19]. Additional information concerning the inclination aspects of orbital debris can be garnered from Figure 6. It depicts orbital period and population distributions against possible orbital inclination values.

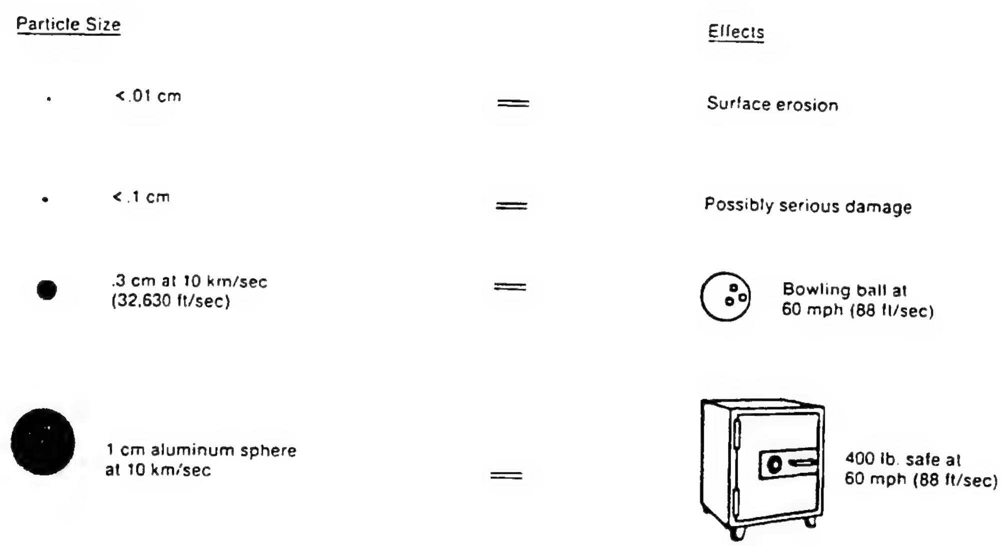


Figure 4. Kinetic Energy and Debris Effects Comparisons. [Ref. 5, p. 10]

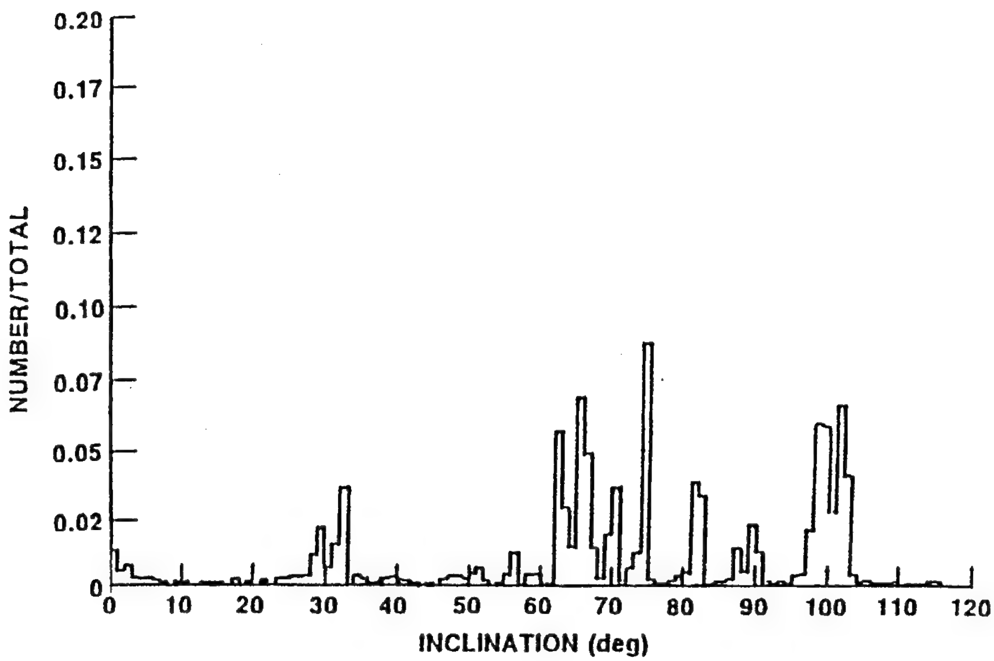


Figure 5. Inclination Distribution of Catalogued Objects. [Ref. 6, p. 85]

TABLE 1. USSPACECOM POPULATION DISTRIBUTION. [REF. 7, P. 19]

Inclination	Period							
	87	95	100	105	110	115	120	TOTAL
10.0 - 20.0	0	1	0	0	0	0	2	3
20.0 - 40.0	22	78	48	65	19	18	40	290
40.0 - 60.0	32	23	18	17	9	30	29	158
60.0 - 70.0	44	68	367	230	129	83	40	961
70.0 - 80.0	18	75	279	34	191	334	11	942
80.0 - 90.0	29	180	523	219	99	43	127	1,220
90.0 - 100.0	57	201	461	183	76	4	19	1,001
100.0 - 110.0	1	6	39	69	152	287	72	626
110.0 - 145.0	0	0	11	4	0	2	4	21
TOTAL	203	632	1,746	821	675	801	344	5,222

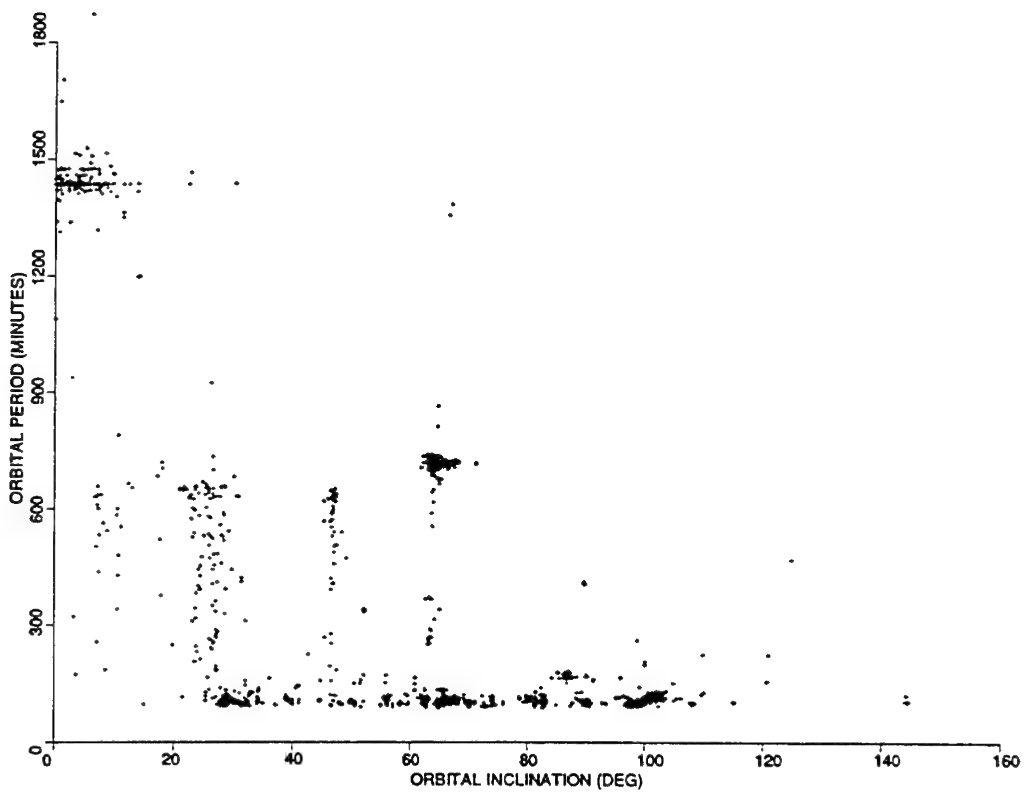


Figure 6. Diagram of Orbital Period vs. Inclination of Catalogued Objects. [Ref 1, p. 3]

Of interest when discussing inclination aspects of space debris is the ability of space debris to produce debris clouds. These occur either upon impact or as a result of satellite break-up or fragmentation. Debris resulting after an explosion initially forms an ellipsoid; it quickly evolves into an irregular, narrow torus about the Earth due to differential velocity in orbital debris. After fragmentation, the debris quickly forms a ring within a narrow band of orbital planes constrained by the changes in inclination. The orbits are also constrained in altitude by changes in the perigee and apogee, normally several hundred kilometers. However, the orbital planes begin to spread apart. Eventually, debris cloud dispersion advances to such an extent that the tracks of the orbiting debris trace a thin shell about the Earth with a hole centered at each pole. [Ref. 6,

p. 9] Additional information on satellite break-up phenomena is presented later in this paper.

Another important parameter used in describing debris is altitude. In the context of this paper, altitude is normally measured in either kilometers (km) or nautical miles (nm), and is defined as the straight line distance between the center of mass of an orbiting object and the surface of the Earth. Similarly, debris also occupies the whole spectrum of LEO altitude ranges. Two illustrations highlight this condition. Figure 7 provides a distribution of objects as a function of altitude. Figure 8 depicts the number of catalogued debris objects with respect to their altitude regime.

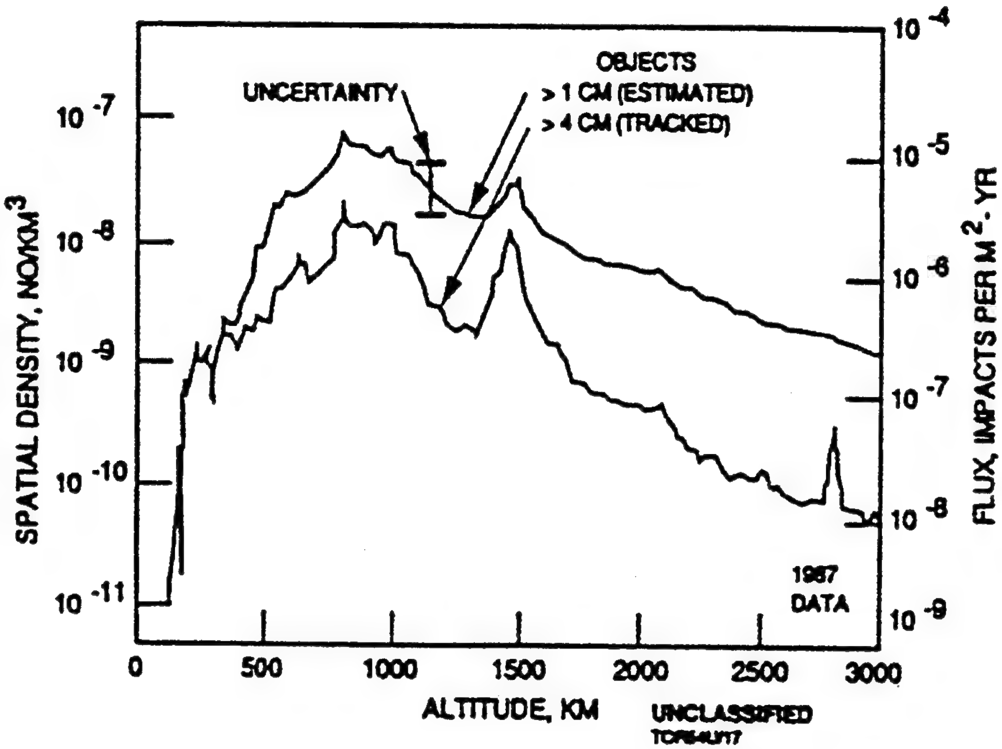


Figure 7. Altitude Distribution of Space Objects. [Ref. 2, p. 706]

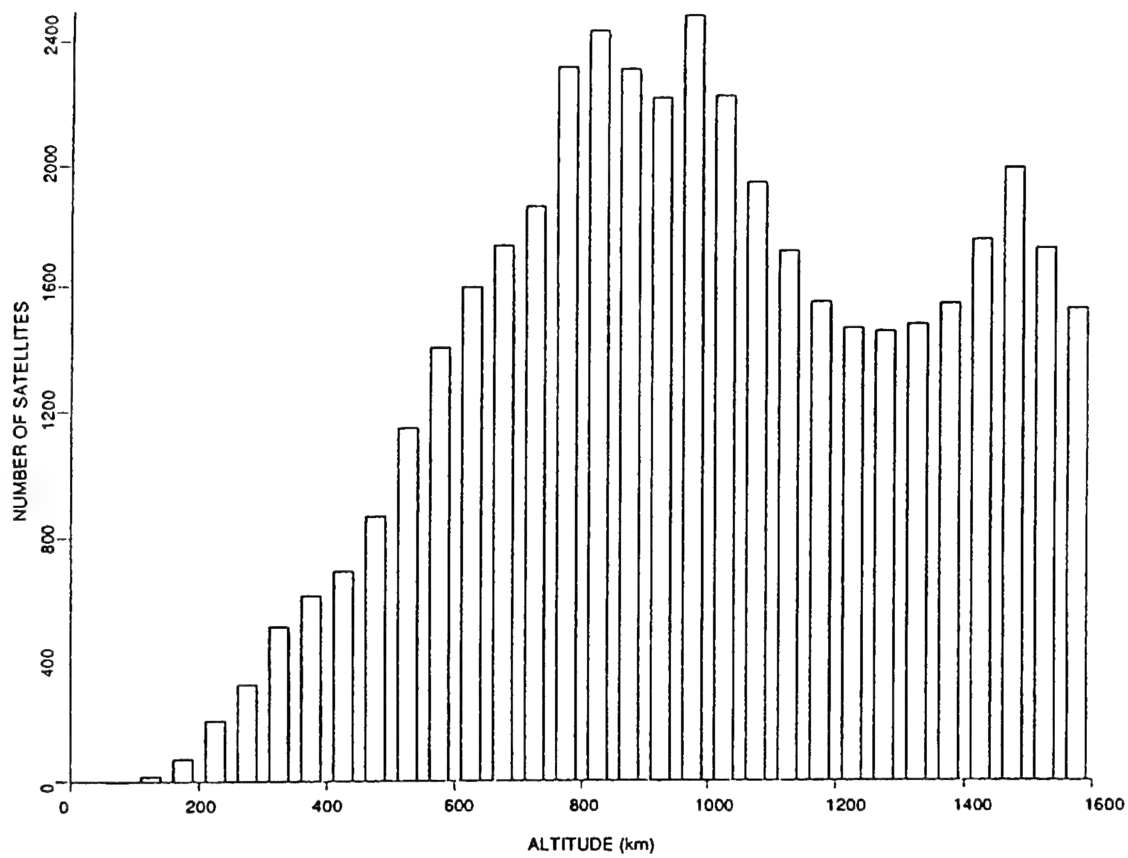


Figure 8. Altitude Regime of Catalogued Objects. [Ref. 1, p. 19]

Depending on several factors, orbital debris lifetimes range anywhere from several hours to several million years. Debris altitude and area-to-mass ratios make significant contributions to the determination of an object's orbital lifetime, as do environmental forces.

In general, an orbiting object falls into progressively lower orbits if the balance between centripetal and centrifugal forces is not maintained. An object losses energy through friction with the upper reaches of the atmosphere and other orbit perturbing forces. Through the conservation of energy, orbital velocity increases as its altitude decreases. Once inside the atmospheric envelope, drag will slow down an object rapidly and cause it to either burn up or de-orbit and fall to Earth.

Orbital lifetimes for objects in elliptical orbits differ significantly from those in circular orbit. For elliptical orbits, the lower the perigee altitude, the greater the atmospheric drag effects. Thus, an object in an elliptical orbit will have a higher apogee decay rate and a shorter on-orbit lifetime than an object in a circular orbit of equal energy.

The natural decay of orbiting debris is also affected by the eleven year solar cycle. High solar activity heats up the atmosphere and causes it to expand and move to higher altitudes. Density at higher altitudes increases and causes objects to decay more rapidly. Additional information on this topic is discussed later in the chapter.

Given these considerations, objects in circular orbits at altitudes between 200 and 400 km typically re-enter the atmosphere within a few months. At higher altitudes, 400 to 900 km, orbital lifetimes can exceed a year or more; at 900 km, lifetimes can be 500 years or more! As altitude increases, the importance of atmospheric drag diminishes. Thus, at GEO, orbital lifetimes are on the order of millions of years. [Ref. 2]

3. Population

The precise number of man-made objects in space is not known. This uncertainty is due to several factors that are discussed later in this paper. Within the past three decades, approximately 23,000 artificial objects have been cataloged. Of these, approximately 7,200 currently remain aloft. Figure 9 presents a breakdown of cataloged debris population; Figure 10 provides a breakdown in terms of numbers of cataloged objects. It would seem that, given the orbits most frequently used, 7,200 objects would not constitute a large crowding problem. In fact, there is an average of 7.51×10^{-9} objects per km^3 in the 300 to 1,500 km altitude regime. However, the numbers do not stop there. Figure 11 illustrates the growth of catalogued objects in space since 1957. Objects put into orbit seldom remain as they were on the ground. Objects shed several items, such as shrouds, lens caps, and nuts. Moreover, most artificial space objects are too small to be detected from the ground using conventional tracking techniques. As previously mentioned, the smallest of the more than 7,200 objects catalogued by USSPACECOM are about 10 cm across. Use of detection methods more sensitive than those employed to

create this catalog has produced dramatically higher estimates of the number of space debris objects. There are now estimated to be about 20 untrackable 1 cm objects and nearly 10,000 untrackable 1 millimeter (mm) objects for every trackable object. Artificial objects as small as 1 micron (10^{-6}) meters, could number 100 trillion; refer to Figures 11 and 12.

a. Current and Projected

The distribution and flux, that is, either the amount of debris passing through a given area of space over time or a given amount of debris passing through an area over a period of time, are dependent on many variables. These variables, discussed below, provide a source for great disparity between current and projected models of the debris environment.

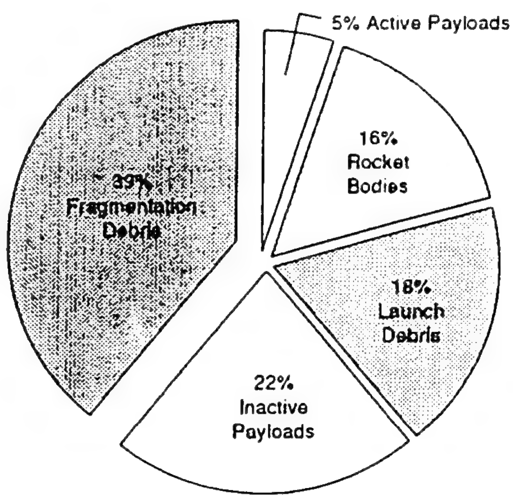


Figure 9. Catalogued Debris Population. [Ref. 4, p. 478]

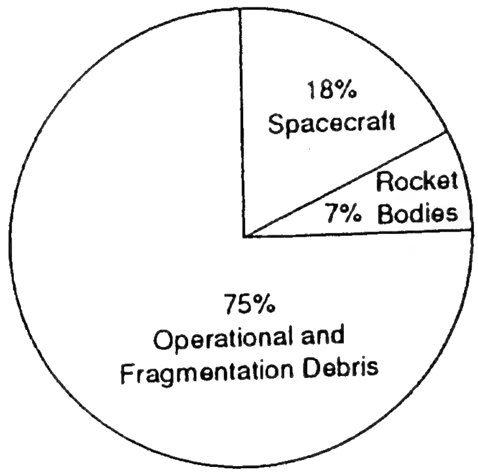


Figure 10. Numbers of Catalogued Objects. [Ref. 4, p. 478]

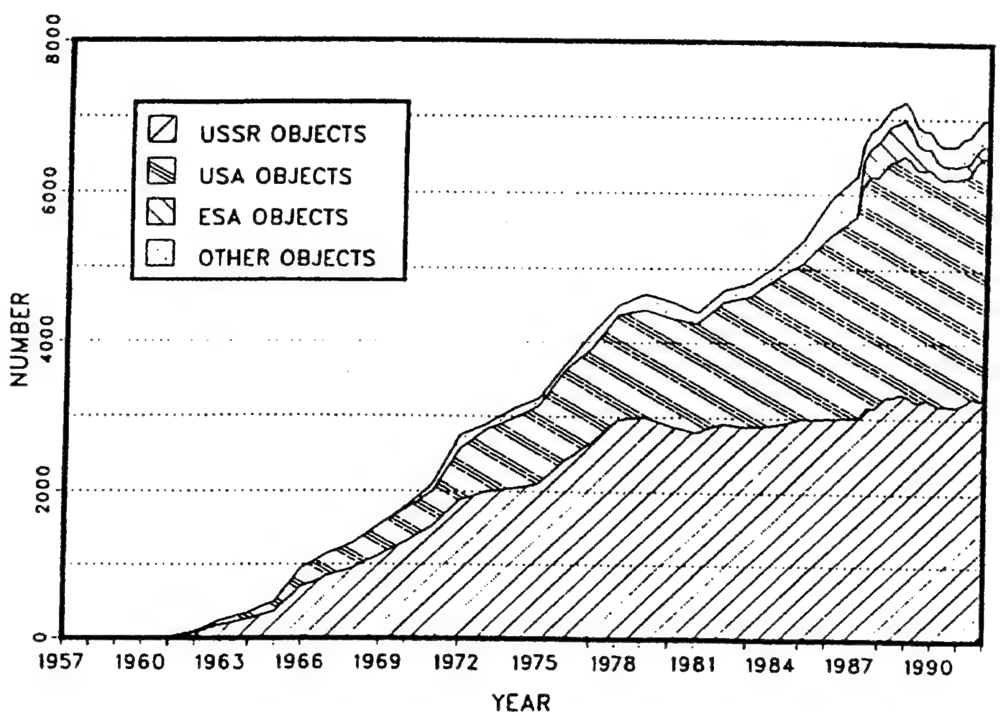


Figure 11. Historical Growth of Catalogued Objects. [Ref. 8, p. 470]

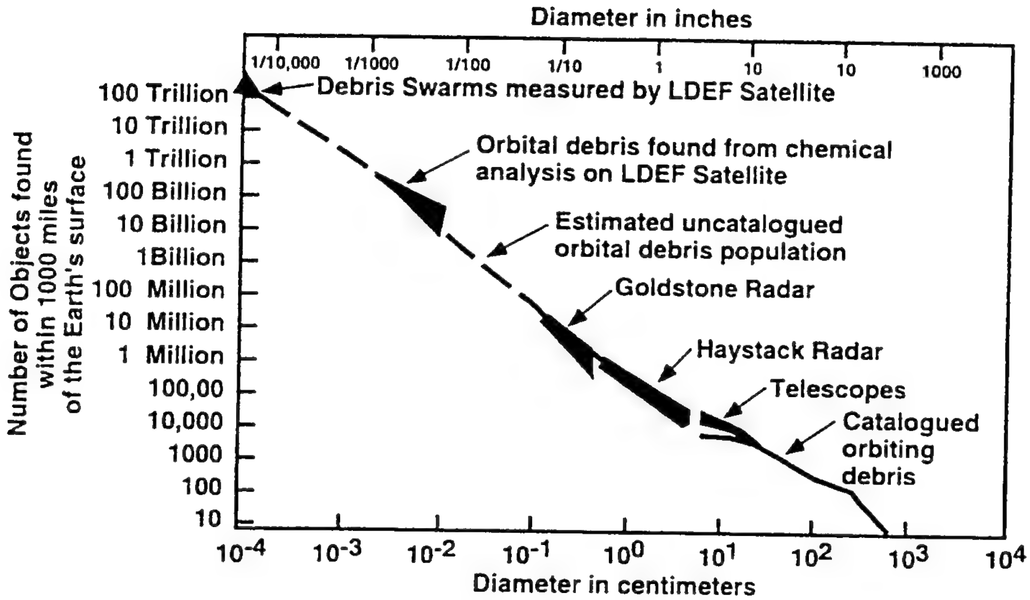


Figure 12. Number of Objects in LEO Measured by Various Methods. [Ref. 9, p. 3]

Figure 13 illustrates the average flux resulting from USSPACECOM's catalogued population. It compares the flux of catalogued objects in LEO, 0-10,000 km regime, with that in GEO, approximately 23,000 km altitude. The average flux in GEO is considerably lower than that in LEO. However, it is important to note that in GEO there is only one natural process, solar wind, which will eventually eliminate an object from this altitude. Although there are fewer, they are there for a longer amount of time. However, by combining the results of other measurement efforts, such as the LDEF and Solar Max, a clearer picture has emerged. Figure 14 provides a summary of the best measurements to date.

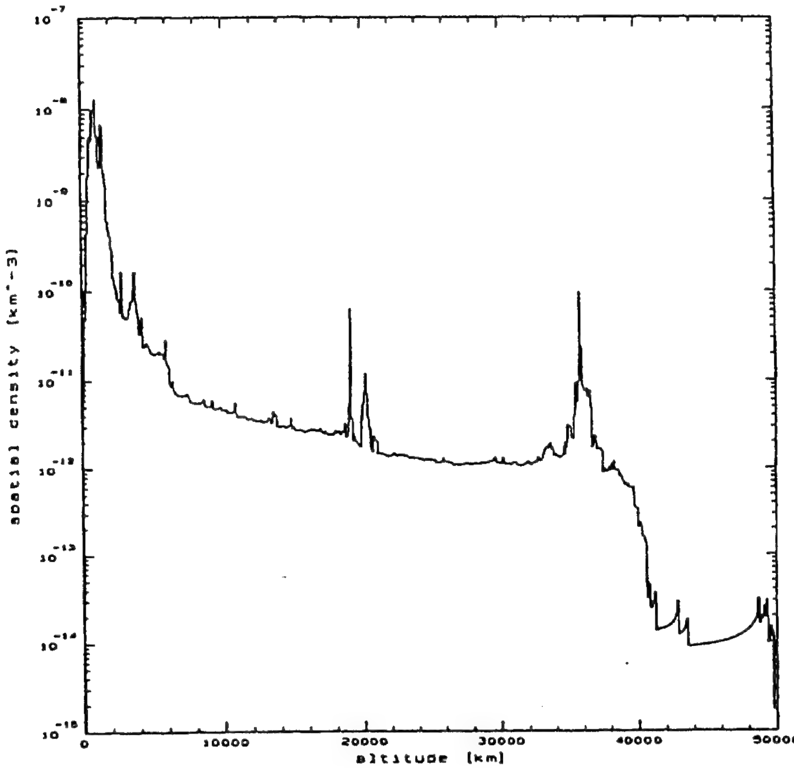


Figure 13. Average Flux of Cataloged Population. [Ref. 10]

The size distribution measured by Haystack, a very sensitive radar, clearly demonstrates that flux significantly increases with decreasing orbital debris size for sizes smaller than 10 cm. Other experiments illustrate that this trend continues to sizes as small as 1 micron; however, because sizes smaller than 1 mm have only been measured at lower altitudes, there is some uncertainty as to how these measurements should be combined with the optical and Haystack measurements, where a larger range of altitudes have been measured. Models predict that the flux of debris smaller than 1 mm should increase with altitude, up to an altitude of at least 1,000 km. The rate of increase depends on the object's source; thus, it is possible that the size distribution at higher altitudes includes a larger flux of smaller debris than that shown in Figure 14.

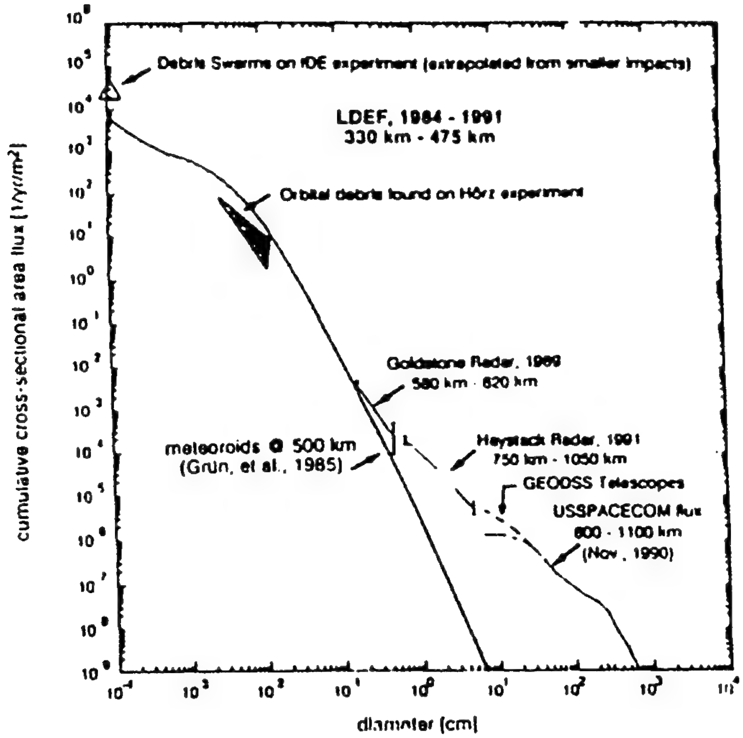


Figure 14. Summary of Best Measurements to Date. [Ref. 11, p. 146]

Moreover, the projected future of the orbital debris population is not promising. Several diagrams evidence growth in different ways. First, there is a historical increase of trackable objects, shown in Figure 15 by orbital regime, and in Figure 16 by originating country. Several models, in different scenarios, show the inevitable increase in the hazard posed by space debris. Figure 17 depicts a mathematical model of current debris flux for various sizes and altitudes. Figure 18 shows projected orbital debris flux under nominal environment and growth conditions. Consequently, there is a projected increase of objects down to the size of 1 cm for the next 20 to 50 years, without the added effects of interactive collisions. Figures 19, 20 and 21 show three different models that depict the long term evolution of debris greater than 1 cm. All three show similar results under similar conditions. In Figure 19, linear rates refer to the

initial population of 1990, and compounded rates to the preceding year. [Ref. 2, p. 636] Figure 20 shows the evolution of the number of objects greater than 1 cm in LEO [Ref. 2, p. 613]. Finally, Figure 21 shows the long term evolution of the population with and without objects less than 10 cm in the basic population. Cumulatively, these diagrams show an increase from approximately 100,000 objects to approximately 500,000 objects within 50 years. As the number of objects increases, respective growth in the mass of objects in space also increases. Figure 22 illustrates the accumulation of mass in LEO and shows the projected accumulation of mass under various traffic scenarios. [Ref. 3, p. 12] In closing, based on several different simulations and models, the projected outlook of the debris environment is undeniable: the continued growth of the debris problem is inevitable if left unchecked.

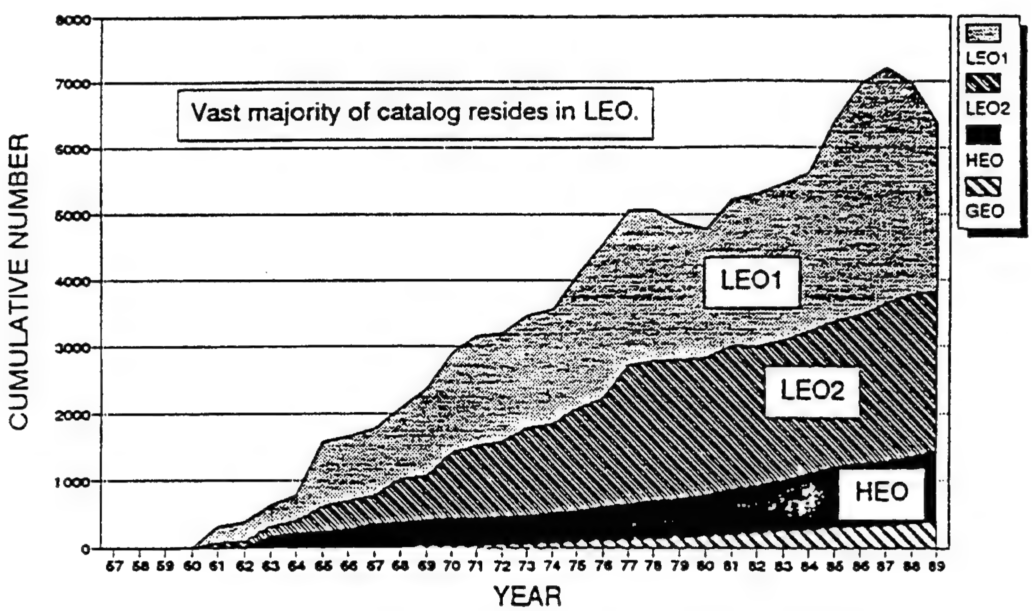


Figure 15. On-orbit Population Growth by orbital Regime. [Ref. 12, p. 127]

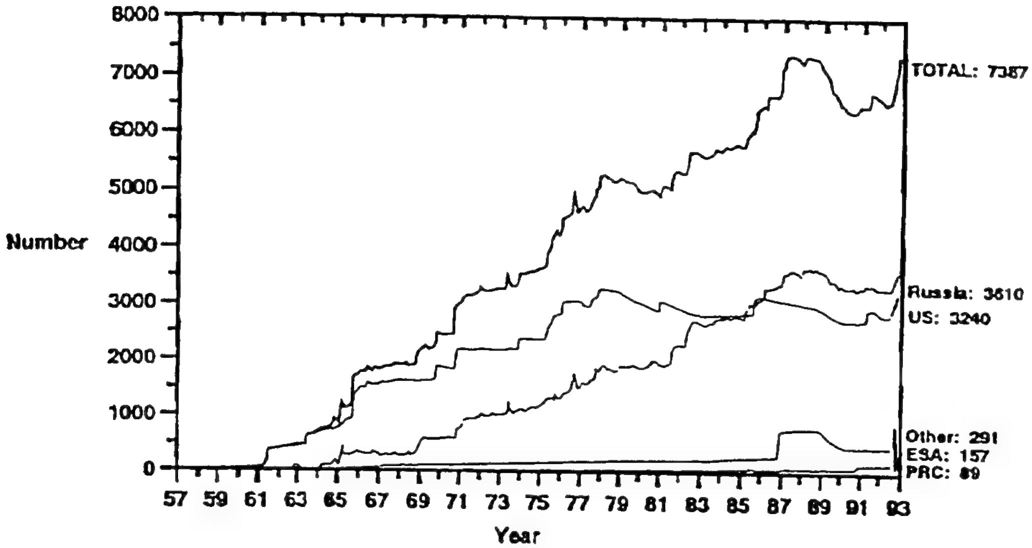


Figure 16. On-Orbit Population Growth by Contributing Country. [Ref. 2]

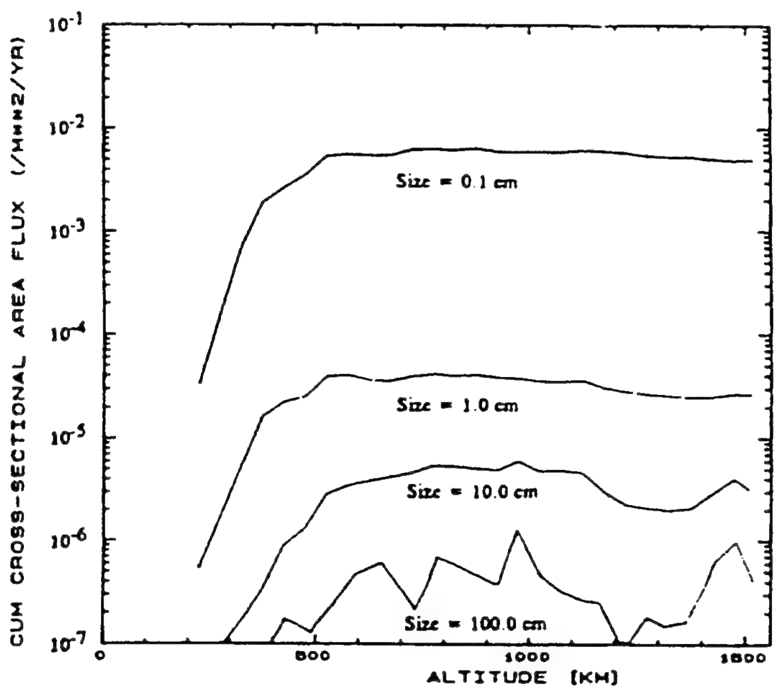


Figure 17. Model Prediction of Small Debris Population. [Ref. 2, p. 282]

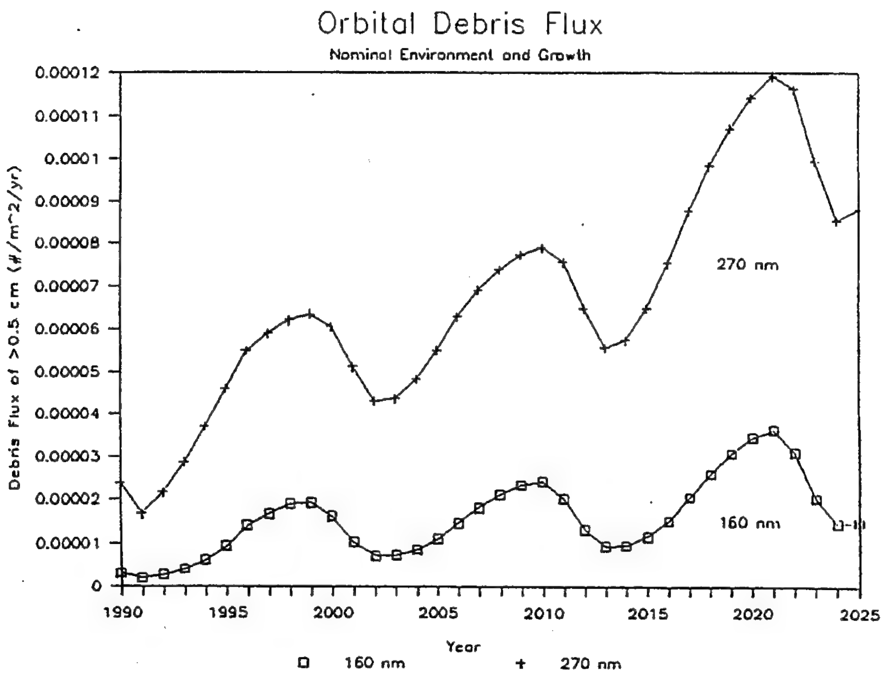


Figure 18. Orbital Debris Flux timeline. [Ref. 13]

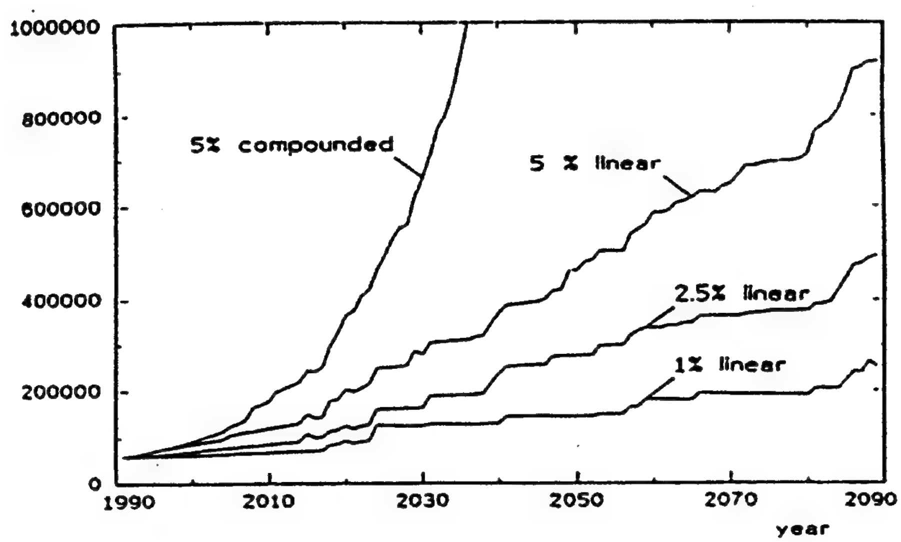


Figure 19. Long Term Evolution of Debris > 1 cm. [Ref. 2, p. 637]

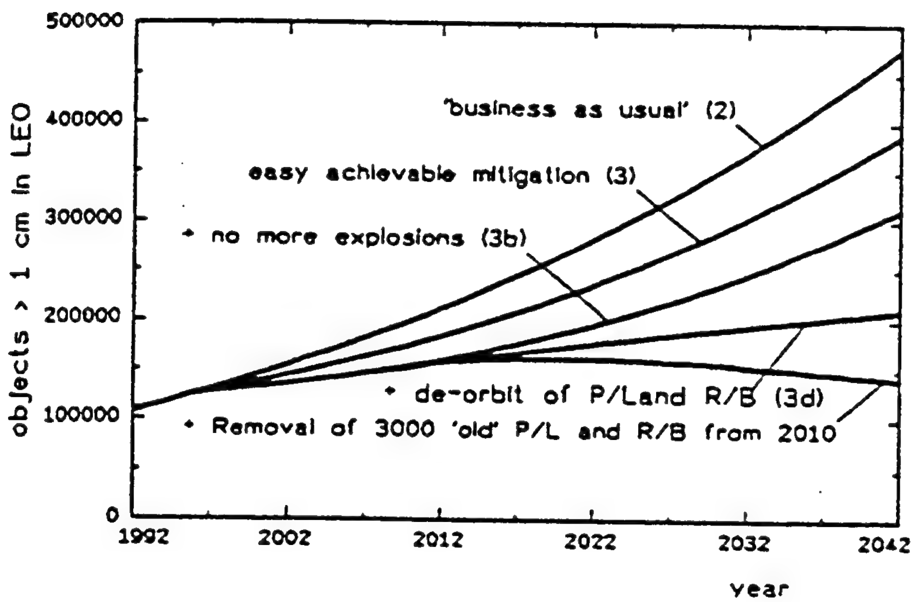


Figure 20. Evolution of the Number of Objects > 1 cm in LEO. [Ref. 2, p. 613]

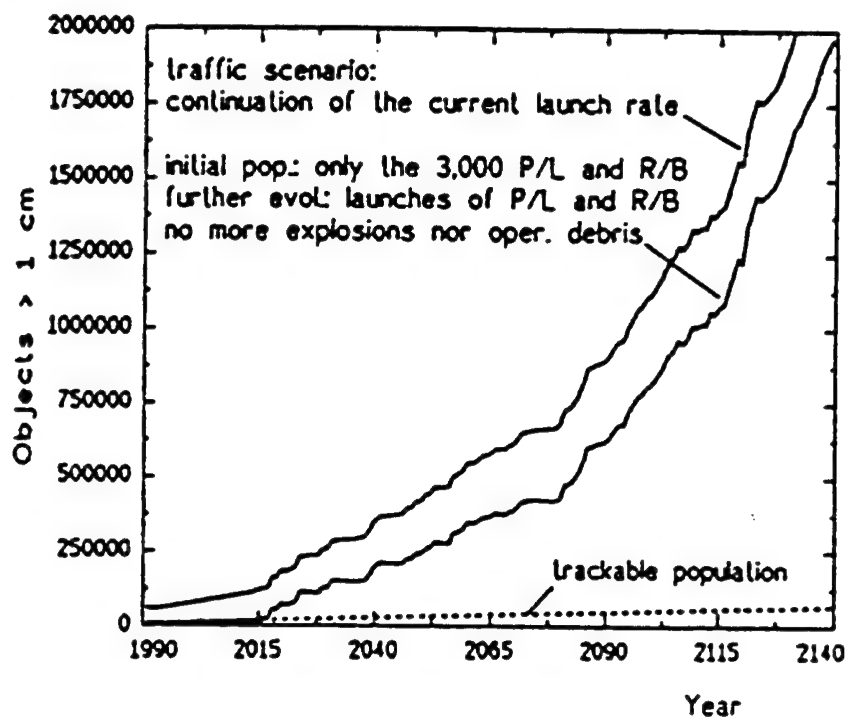


Figure 21. Long Term Evolution of the Population With and Without Objects < 10 cm. [Ref. 2, p. 601]

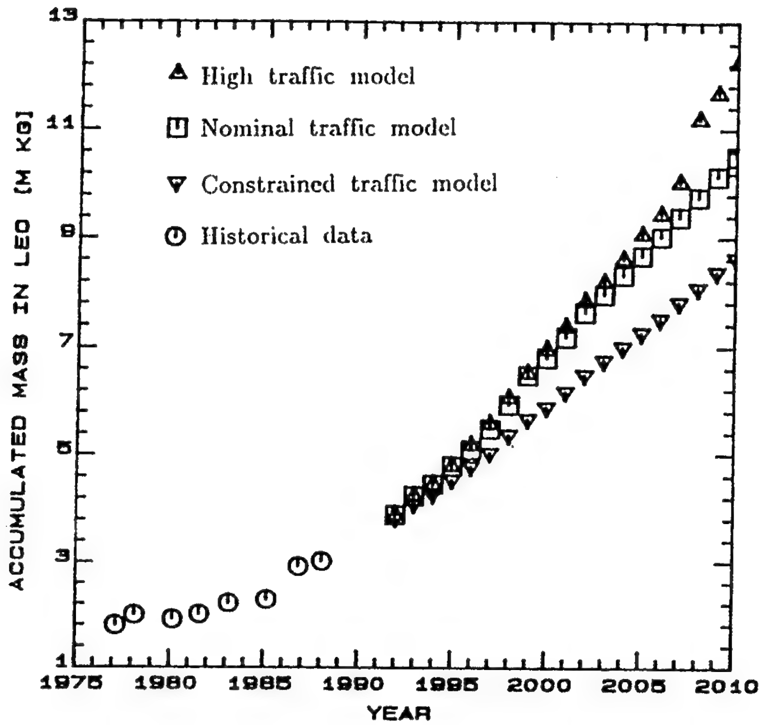


Figure 22. Projected Growth of Accumulated Mass in LEO. [Ref. 3, p. 13]

b. Degree of Uncertainty

Each technique for measurement and subsequent modeling has a limit. They can be limited by the area and time of sampling, and limited as well by the sensitivity of a sensor. When the results of all sensors (models) are taken into account, a clearer understanding of the size distribution emerges. In general, there is a high degree of uncertainty in our knowledge about the current debris environment and our abiilty to develop accurate projections of the future environment.

Experts caution that much uncertainty exists in our knowledge of the exact location, amount and size of debris, as well as how serious the problem may become in the future. This uncertainty is caused by factors such as our limited ability to measure and actually validate the number and size of particles, a lack of predictability in the level

of future space activities, and the indeterminate causes of breakup events as major debris sources.

Today, it is generally accepted that the LEO environment is adequately measured for orbital debris sizes larger than 10 cm. Based on this data, the population density of the measured debris is known to an uncertainty factor of between two and five. However, for debris 0.01 cm and below, there are no confirmed measurements. The estimates given here are based on a linear extrapolation which has an uncertainty factor of 10. [Ref. 3, p. 5]

The reader is asked to keep in mind this perennial degree of uncertainty involved with the debris problem. The factors described above, contributing to this uncertainty, affect every facet of the debris situation. The first factor, that of limited measurement capabilities, obviously affects our ability to determine exact numbers on debris. This lack of specificity is important because actions and predictions based on these limited measurements allow for a wide margin of error. The other two factors also have the same effect: to create a sense of uncertainty and doubt. From this, it is easy to see why debris simulations require many assumptions in order to present current and projected evolutionary scenarios.

For instance, note Figure 23. It depicts a graphical representation of three case scenarios. Case 1 is "business as usual". That is, it assumes that the world launch rate remains at the current 100 launches a year. Case 2 assumes the same condition, but adds the assumption that all chemical explosions are eliminated by the year 2000. Case 3 assumes the same conditions found in Case 2, but adds two conditions: by the year 2000, rocket bodies will be required to re-enter after payload delivery; and by 2030, payloads will be required to be removed from orbit after the end of their operational life. [Ref. 11, p. 146] This model relies heavily on one assumption: the future global launch rate. A change in this parameter would obviously have an impact on the output of the simulation. What if the world launch rate changes dramatically? Action taken based upon the preceding model would produce highly unsatisfactory results. In a recent *Space News*

article, a study was released showing an increased market for small satellites. Nearly doubling in size, the larger market inevitably means more launches and more possible sources of space debris.

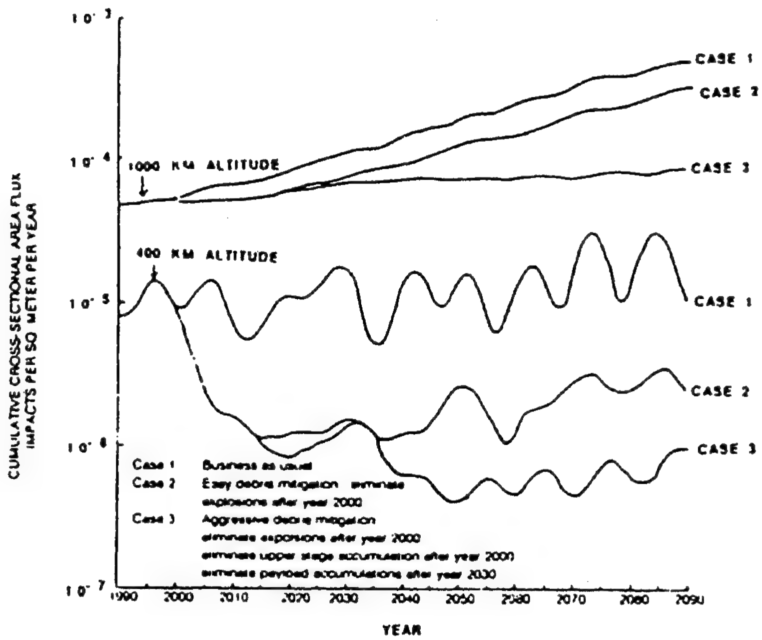


Figure 23. Example of the Predicted Change in the Debris Environment Under Various Scenarious. [Ref. 11, p. 145]

4. Sources of Orbital Debris

In the course of this paper, some sources of debris have already been mentioned or implied. Figure 24 depicts a breakdown of some of the major causes for debris. In this section, four general categories of debris sources are investigated.

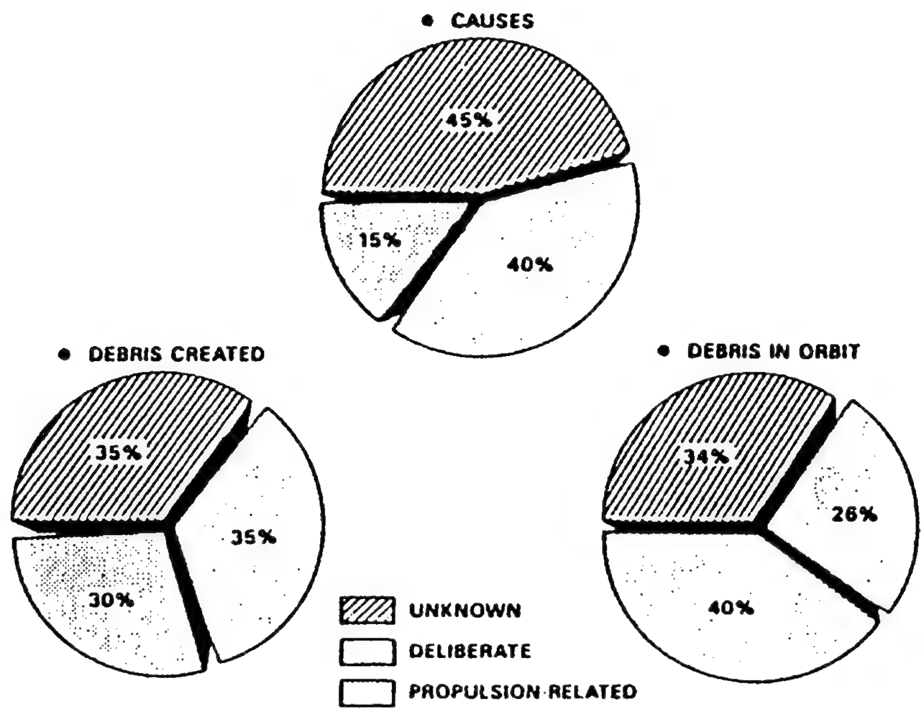


Figure 24. Causes of On-orbit Fragmentations and Debris. [Ref. 1, p. 23]

a. Satellite Deterioration

A little understood source of space debris is the gradual deterioration of old spacecraft and rocket bodies. This deterioration is the source of the very small objects alluded to earlier.

Two of the major processes involved with the generation of this type of debris are atomic oxygen contamination and solar radiation levels. These two catalysts, atomic oxygen and radiation, combine to bring about the disintegration of spacecraft surfaces. Atomic oxygen is suspected of causing erosion of protective coatings, paints and composite structures in a spacecraft. Experiments flown on STS-5 and STS-8 show that atomic oxygen may be an even greater hazard to spacecraft than previously believed;

data suggests that graphite epoxy composite structures can lose up to 0.15 cm of thickness within 30 years due to atomic oxygen alone. [Ref. 1, p. 12]

Radiation may cause the breakdown of bonding compounds plus the embrittlement of protective thin films and coverings. Also, repeated heating by solar radiation can induce thermal stresses and result in structural failures of large satellites.

b. Satellite Fragmentation

Satellite fragmentation is the largest source of man-made space debris. It accounts for over 1/3 of all satellites in the catalog, and composes almost 1/2 of the known Earth satellite population. Refer to Figure 25.

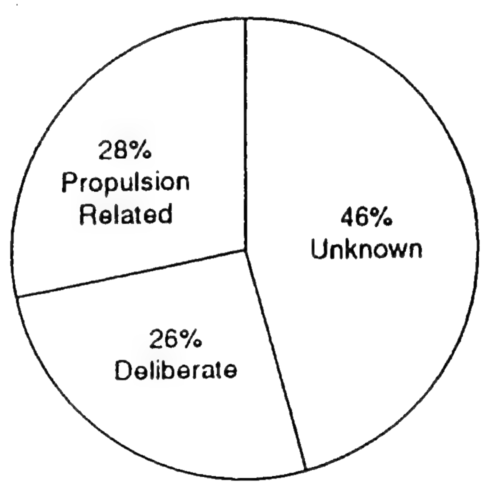


Figure 25. Causes of Debris by Fragmentation. [Ref. 4, p. 478]

As of today, nearly 130 satellites have fragmented in space since the first breakup, detected in 1961. Causes for satellite breakups have been categorized into three general groupings: those caused by deliberate actions, by accidental propulsion-related events, and by unknown causes. [Ref. 1, p. 13] This last group is the largest; it accounts for up to 45% of all fragmentations. [Ref. 3, p. 7] This unknown is a direct reflection of

our inability to select a single high probability cause for a satellite breakup. Figure 26 illustrates the relative influence of these breakup groups at five year intervals.

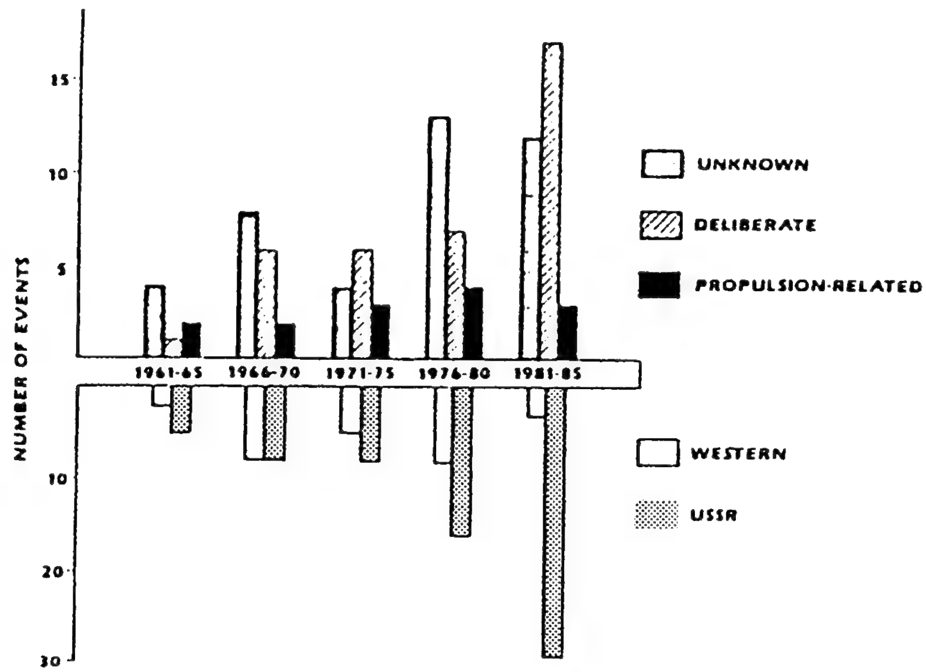


Figure 26. Rate of Satellite Fragmentations. [Ref. 1, p. 13]

c. Launch and Operations Activities

Operational debris is produced during nearly every stage of orbital operations. This includes launch vehicle staging and operations; payload separation; payload activation; payload operations; and payload de-orbits. Exclusive of fragmentation events, an average of three trackable objects are catalogued for every launch. For example, the KOSMOS 2048 produced eight pieces of debris: three pieces during payload separation and activation; three pieces during payload de-orbit preparation; and two pieces during payload de-orbit operations. [Ref. 6, p. 14]

d. Solid Propellant Particles

Another source of small particles is the operation of solid rocket motors, which are normally used as final transfer stages on GEO missions. Current solid rocket

technology often employs significant quantities of aluminum mixed with the propellant in order to dampen burn rate instabilities. However, during the burning process, large numbers of aluminum oxide particles are formed and ejected through a wide range of flight path angles at velocities up to 4 km/s. These particles are larger than 10 mm, but as many as 1,020 may be created during the firing of a single solid rocket motor! [Ref. 14, p. 3-7]

More recently, focus has been drawn to a potentially more dangerous side-effect of solid rocket motors. Ground tests indicate that a smaller number of 1 cm or larger particles are also ejected during nominal burns. These particles, which have a lower characteristic velocity and smaller area-to-mass ratio, may be longer lived and may pose a greater threat than the smaller aluminum oxide particles. [Ref. 3]

5. Sinks of Orbital Debris

a. Environmental Forces Effecting Debris

In general, the LEO environment benefits from the natural cleansing processes associated with its proximity to Earth; GEO to a lesser degree. Figure 27 illustrates the number of cataloged satellite decays.

Orbital decay is a natural sink for the removal of space debris and can be caused in three ways. The first is atmospheric drag, a phenomenon which has been alluded to previously. Below 500 km, the density of the atmosphere is sufficient to affect the orbital velocity of an object. At higher altitudes, atmospheric effects are less significant. The rate at which a satellite losses altitude is a function of its mass and its average cross-sectional area impinging on the atmosphere. [Ref. 14, p. 3-8]

A second natural sink is solar-lunar perturbations. This type of sink is of primary importance to objects in highly elliptical orbits. Gravitational effects of the Sun and Moon produce forces that can cause the perigee of the orbit to either rise or fall. Figure 28 shows perigee altitude history affected by lunar/solar cycles.

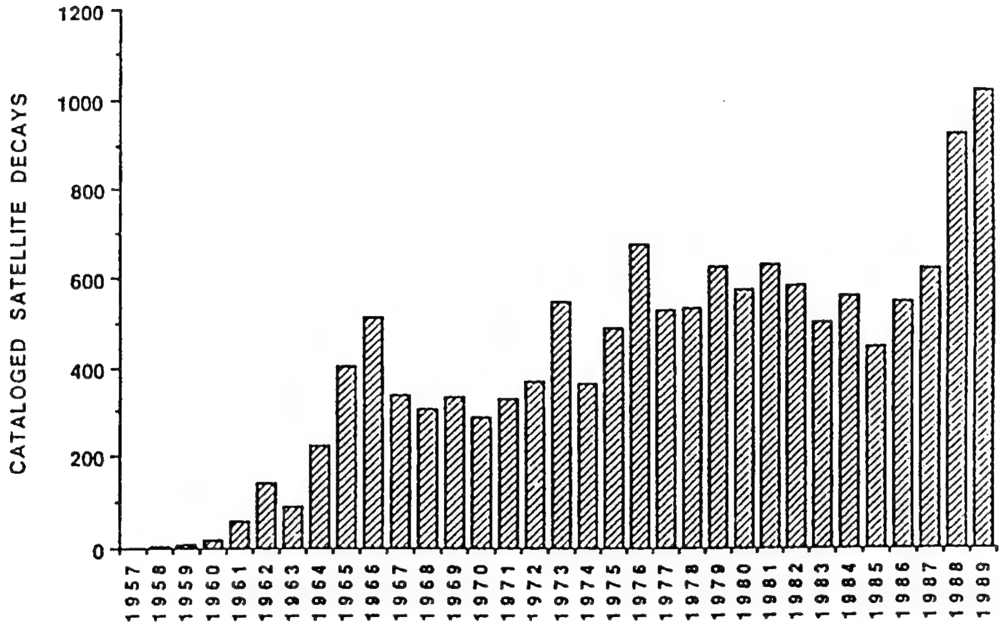


Figure 27. Cataloged Satellite Delays. [Ref. 5, p. 30]

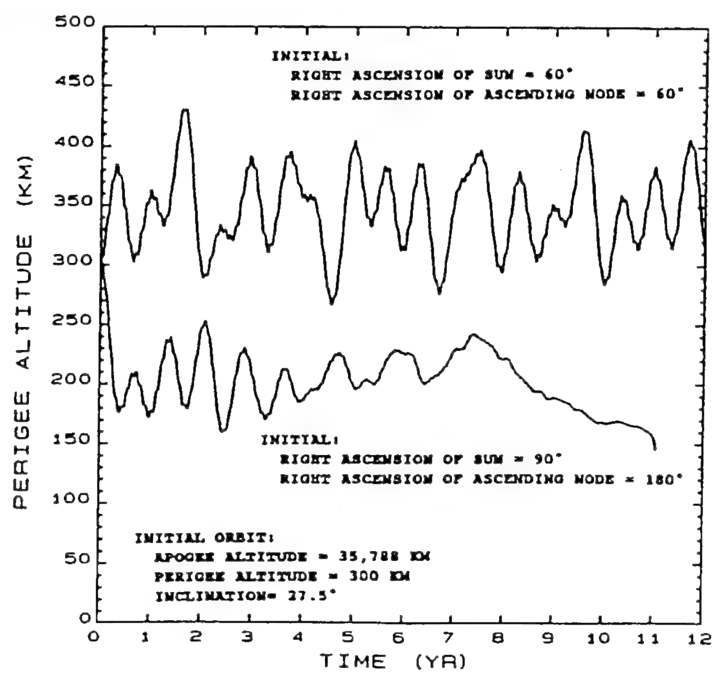


Figure 28. Perigee Altitude History Affected by Lunar/Solar Cycles. [Ref. 9]

The third, and less prominent sink effect, is that of solar pressure on a satellite. In essence, striking photons cause orbiting objects to slow down. Obviously, the effect is negligible for large bodied objects; however, for particles of a few grams or less, it can induce rapid orbital decay. [Ref. 1, p.6]

b. Retrieval and De-orbits

Retrieval and de-orbiting are man-made methods of accomplishing the same goal as above. They both serve to remove payloads from their active orbits at the end of their operational lifetime.

Of the two, de-orbiting is a preferred method; it is less difficult and less expensive than retrieval. De-orbiting is a feasible solution for payloads in LEO and GEO. De-orbiting of a satellite is a planned event; de-orbit considerations must be incorporated into the overall mission design from the beginning. Through a series of controlled burns or through the use of drag inducing devices, payloads are forced into a lower altitude that facilitates their eventual re-entry to Earth. In GEO, another option exists. Instead of de-orbiting towards the Earth, inactive satellites are boosted into higher orbits. This practice is called removing a satellite into a 'disposal' orbit. Preliminary studies indicate that the orbit needs to be raised on the order of 200 km in order to serve its intended purpose. Of course, both these options are expensive by nature; they require substantial amounts of propellant or fuel in order to properly execute. Cost effectiveness studies would be necessary in order to minimize associated costs with either technique.

Retrieval is only reasonable for larger objects because of the necessary rendezvous maneuvers required. Essentially, satellites are physically removed from their orbit by means of a second spacecraft system or a remover device. The strategy for the removal of objects from Earth orbits will always consist basically of successive rendezvous and de-orbit maneuvers. Presently, this manner of removing satellites is only feasible for LEO objects, one at a time. Recent research is looking into the possibility of economically removing numerous large objects from orbit by means of energy transfers. The concept involves using space tethers for energy transfers; once an object is roped by

the tether of a remover device, the remover will climb to a higher altitude while the debris object will decay to a lower altitude. Through successive 'ropings', it would be possible to retrieve numerous large objects in a more economical manner. [Ref. 12, p. 197] Both these strategies are again discussed in Chapter IV.

6. Debris Effects

Space debris presents a complex issue. Description of the physical characteristics and processes of space debris, as well as our lack of precise measurements, confirm this. From a systems perspective, this complex problem suggests that there is a high degree of inter-relatedness between the many processes surrounding space debris. It would seem this is the very nature of space itself. What is implied, and was previously alluded to, is that most of the space debris issue revolves around cause-effect relationships. For instance, more satellites in space leads to overcrowding conditions in select orbits; the effect of this condition is the increased potential for collisions between objects. Or, the reverse is true; removing debris, by natural or man-made techniques, certainly causes less saturation of the environment and results in a lower probability of collision among objects.

Having presented the various bits of information describing space debris, it is now appropriate to focus on what happens when it is all put together. To use an analogy, 'snapshots', or pieces of a puzzle, have been presented. Now, focus on the outcomes after seeing the 'whole' picture; what do the sum of the parts equal?

a. Hypervelocity Impacts

This is something that has been alluded to all along: the danger of objects colliding with one another at high velocities. In the context of this paper, hypervelocity impacts are those impacts which describe collisions between objects in orbit. They are characterized by large explosive energies. Scientists are particularly interested in hypervelocity impacts occurring between the ranges of 7 to 15 km/sec; this is representative of space debris induced collisions. Hypervelocity is operationally defined in those studies as impact speed high enough to create impact sites where the target

material appears to have flowed in a fluid or molten state to mold the final crater shape. Laboratory impacts into glass indicates that this requires impact speeds in excess of about 7 km/s. [Ref. 12, p. 294] Under these conditions, a hypervelocity impact will generate a cloud of bumper and projectile debris that can contain solid fragments, liquid, or vapor particles. Dynamics of a hypervelocity impact are illustrated in Chapter IV.

Impacts are at the very heart of the space debris issue. The threat of objects colliding in space is of utmost concern. Specifically, those collisions which may occur between a useful satellite and an orbiting piece of debris. Concerns are justly founded: given the energies associated with orbiting objects, even the smallest of debris particles affects satellites; larger pieces can utterly destroy a satellite.

b. Collisional Cascading

This is truly a vicious cycle of destruction. The theory stipulates that at the moment of critical population density, an irreversible chain reaction of collision events takes place creating increasing levels of space debris; the cycle is perpetuated as the creation of more debris particles creates more collisions, and so on, ad infinitum. Critical population density is reached when that population will produce fragments from random collisions at an increasing rate and at a rate that is greater than the rate of removal by natural processes. [Ref. 15] Refer to Figure 29.

In 1978, collisional cascading was predicted to be an important source of new debris, possibly before the year 2,000. Some critics argue that collisional cascading is happening now. Dr. Kessler, from NASA's Johnson Space Center (JSC), concluded in a recent paper that analysis indicates that certain regions of low Earth orbit are already unstable. He claims that if nothing more is added to the unstable regions, the rate of debris growth will be slow, accounting for one collisional breakup per 10 to 20 years. If this is not the case, these unstable regions will expand, causing breakup rates to increase to every 2.5 to 5 years. [Ref. 15] Figure 30 shows the long term evolution of all objects greater than 1 cm due to collisional cascading effects described by Dr. Kessler.

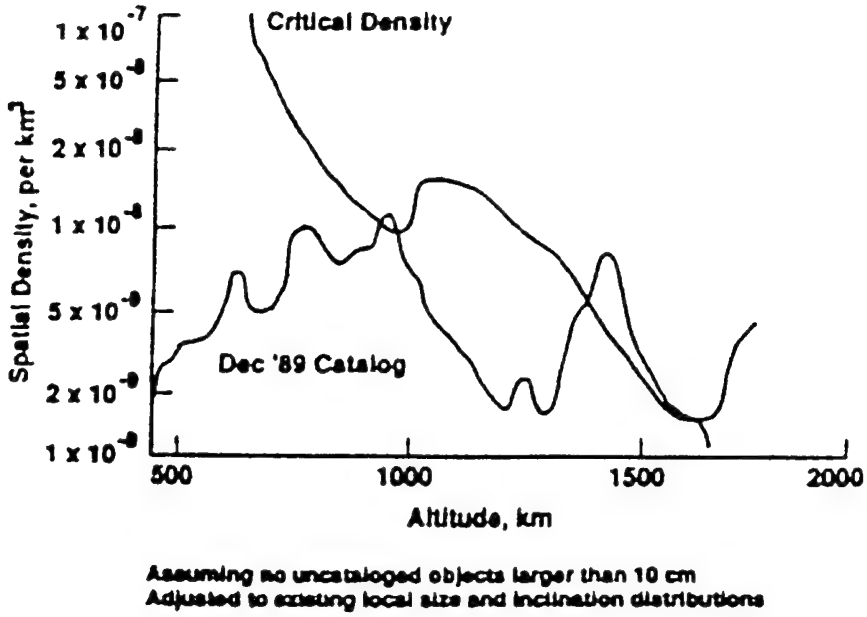


Figure 29. Critical Density Diagram. [Ref. 16, p. 8]

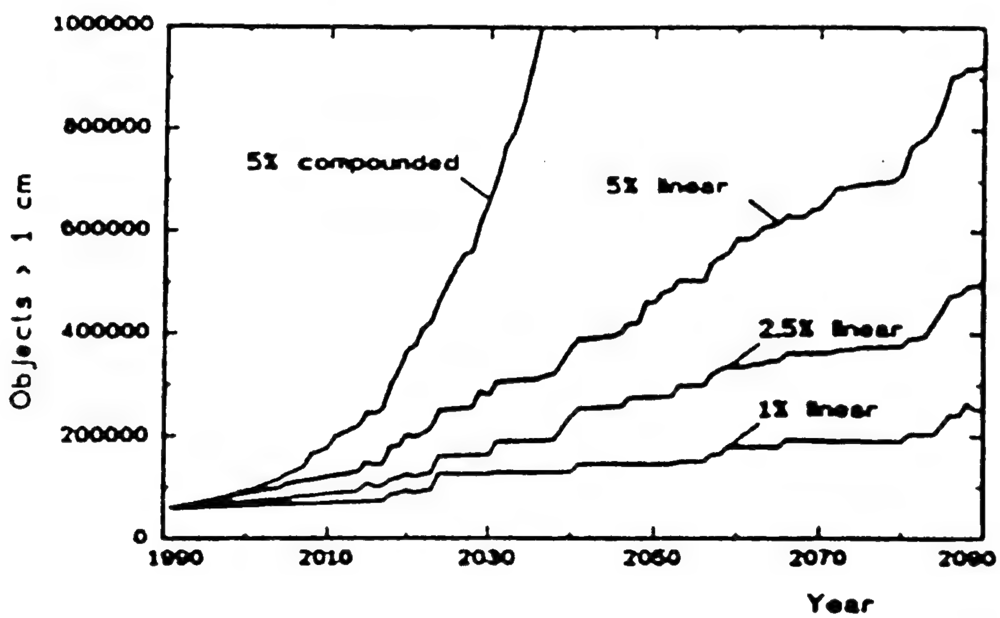


Figure 30. Long Term Evolution of All Objects > 1cm Due to Collision Cascading Effects. [Ref. 16, p. 8]

Figure 31 also shows an exponential increase of the population due to collision chain reaction effects.

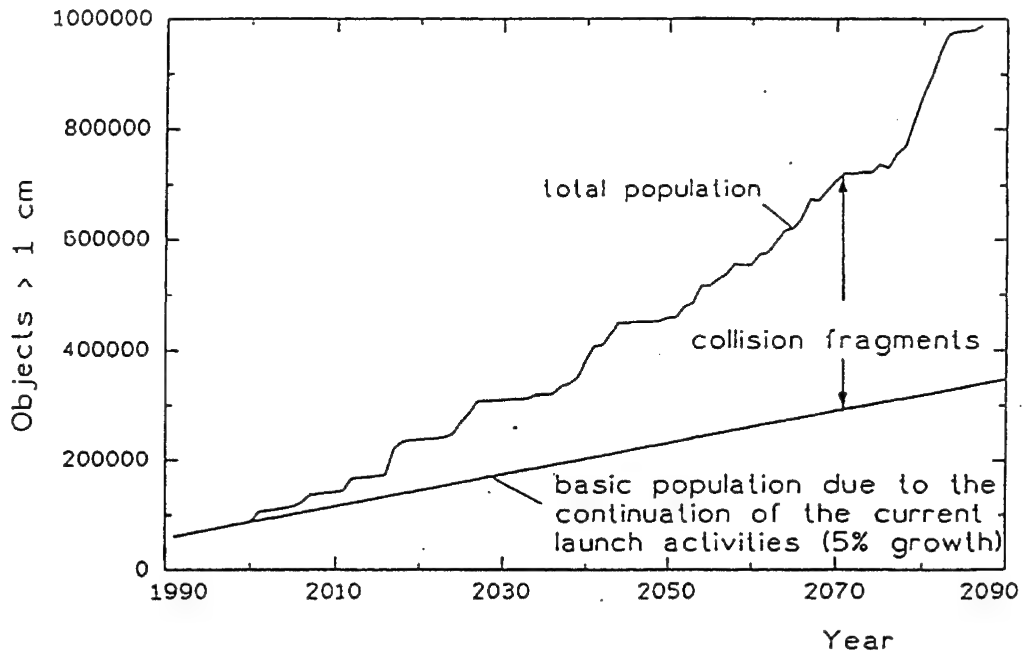


Figure 31. Increase in Population Due to Collision Cascading Effects. [Ref. 17]

c. Current Issues

The problem of space debris is not as far removed from our daily lives as one would anticipate. Not only does space debris pose a hazard to satellites, but it has recently been noted that it is affecting the observational efforts of several astronomers. Space debris often corrupts celestial photographs with long exposure times. There have also been cases of confusion about whether an object under study is in actuality of scientific concern or a piece of debris. As the space debris population grows, so does its ability to reflect light. This has the end effect of causing sensitive instruments to malfunction or take erroneous readings. [Ref. 3, p. 14]

B. RECOGNIZING THE THREAT

It appears to be that the greatest challenge in resolving the debris issue is the recognition of it as a genuine threat to present and future space activity. One of the major factors contributing to this misperception is the sheer immensity of space itself.

By nature, mankind is perfectly adapted to recognize and respond to threats that come in the form of sudden, dramatic events. Today, primary threats to our collective well-being are slow, gradual developments arising from processes that are complex both in detail and in dynamic. [Ref. 18, p. 367]

Such is the case with orbital debris. Failure to perceive the symptoms of this gradual development will have severe consequences affecting all facets of future space activities. Presently, there are several arguments which may influence one's perception of the space debris threat.

1. The LEO Environment

"Well, it's not that big a problem." Untrue; evidence has been provided to indicate that it is an issue of growing concern; the extent of which will be discussed in the next chapter. Consequently, danger to a spacecraft also increases. Figures 32 and 33 corroborate this fact. Figure 32 shows the cumulative risk to a 2,000 m^2 space vehicle over a 30 year period, due to the debris environment model flux of all objects larger than 10 cm. Figure 33 indicates a family of Monte Carlo runs for continuing present practices and launch rates. Note that there is a large uncertainty both as to when the process might start and as to how it might progress. [Ref. 2, p. 629] Nonetheless, despite these inherent uncertainties, one can still ascertain that spacecraft will be at greater risk of collision as conditions worsen.

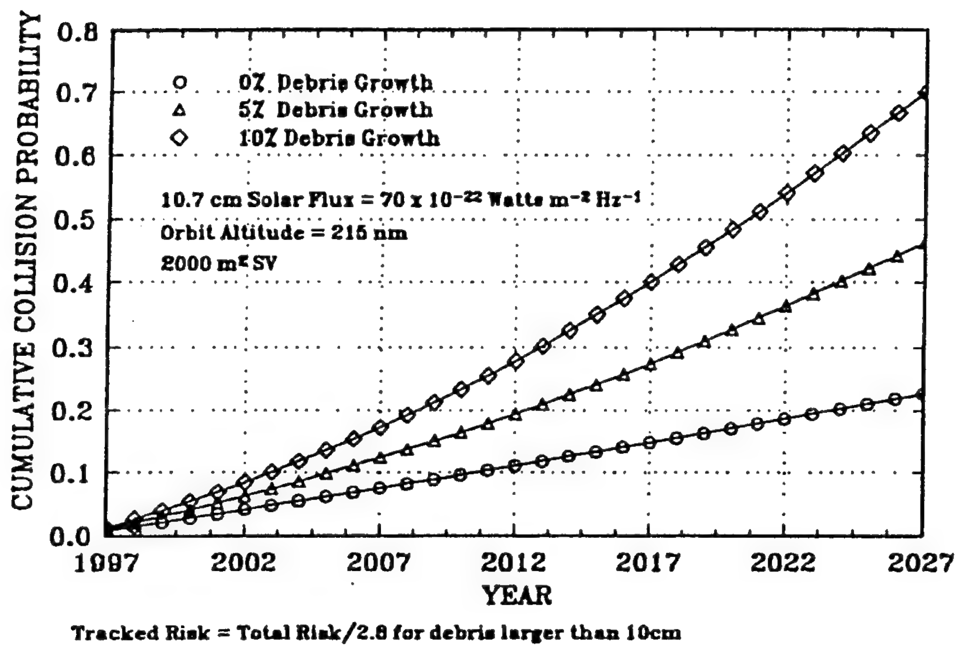


Figure 32. Cumulative Space Vehicle Collision Probability for Debris objects > 10cm. [Ref. 19, p. 4]

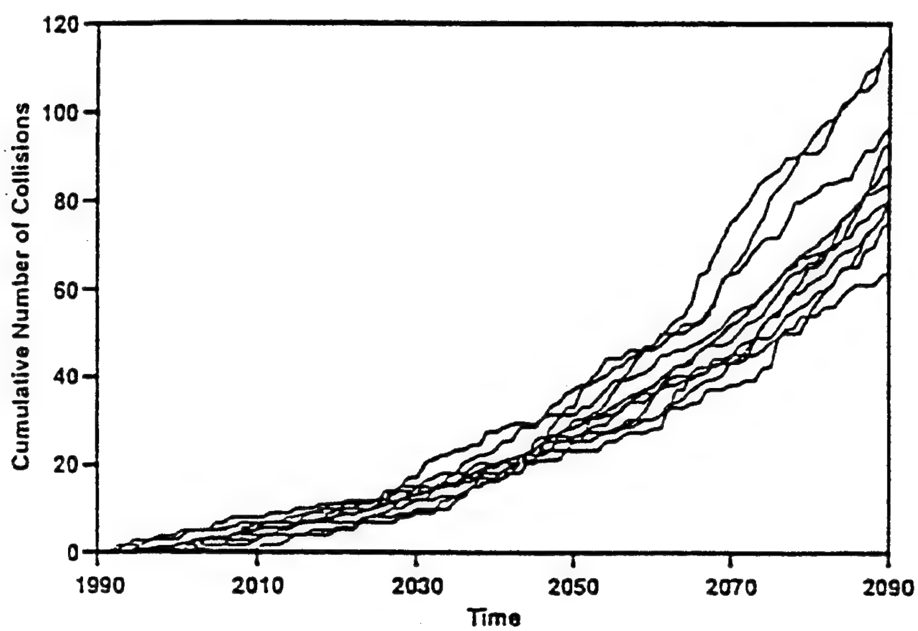


Figure 33. Monte Carlo Expectation of Collisions Among Satellites under Present Operating Practices. [Ref. 2, p. 629]

LEO debris objects are of paramount concern, because a greater threat exists at the LEO range of altitudes. This threat manifests itself in the following manner: more overcrowding conditions create a large possibility of collision, and collisions will be of a higher magnitude than in GEO. Also, the greatest relative velocities between orbiting objects occur at LEO. Since GEO velocities are lower, the danger of impact is smaller and the possible consequences are of less immediate concern than in LEO.

2. Implications: What's in Jeopardy

"OK, we don't stand to lose anything of importance." Again, untrue. LEO contains a myriad of crucial military and commercial satellite services. Its accessibility and orbit characteristics provide several benefits to its users. Ongoing LEO missions include communication, navigation, meteorology and geodesy services. From a military perspective, surveillance, reconnaissance and attack warning capabilities exist. As one can imagine, the loss of any one of these to space debris could have a direct impact on everyone concerned. Loss of these satellites due to collisions seems very likely to occur. Again, simulations indicate that a fairly low collision rate may lead to a collision at a moderate confidence level within several decades. Figure 34 plots four curves that clearly quantify the effects of differing collision rates on the likelihood of a collision over time. [Ref. 20, p. 498]

3. Historical Perspective

"Hey, nothing's happened so far." In a meeting hosted by NASA JSC in 1982, a representative of a satellite operator clearly voiced this position: why should we worry about the space debris problem when in the last 25 years of experience no satellite has been known to have been seriously disabled by space debris [Ref. 1, p. 7]. Though he may have been correct, his assessment is short-sighted. Most experts agree that space debris currently poses only a slight hazard to space operations. However, all concur that unless space activity philosophies are fundamentally modified, a serious problem will develop.

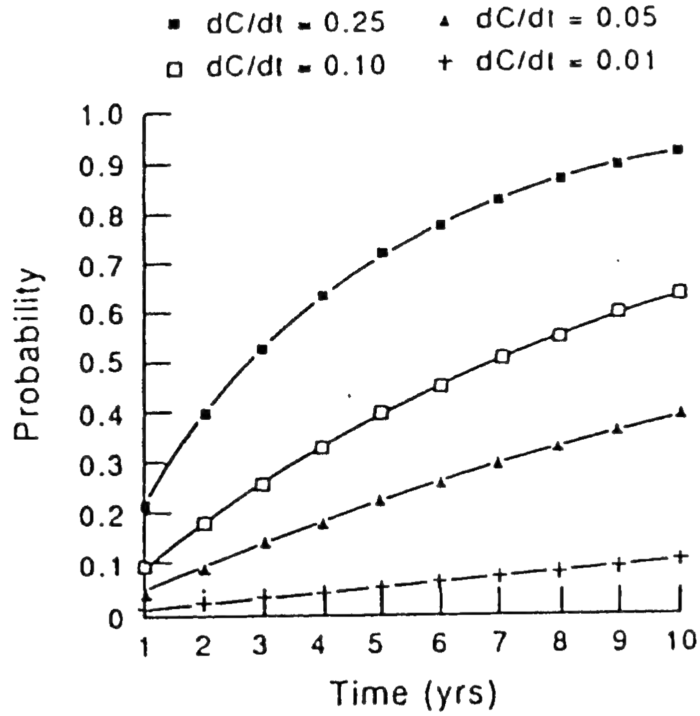


Figure 34. Current Predicted Collision Rate. [REf. 20, p. 498]

Keep in mind the following: some of the causes for past satellite failures are still unknown. Of all the known satellite fragmentations, only the cause of 45% of them has been determined [Ref. 1, p. 22]. Although several possible reasons for these unexplained fragmentations exist, space debris as a cause cannot be discounted. For instance, one recent study points toward the likelihood that there has been at least one collision-induced breakup in LEO [Ref. 20, p. 499].

In another closely related argument, several from the space community argue that space debris should not be of pressing concern because past launch rate failures far exceed space debris related failures. From an economic perspective, the Department of Defense (DoD) relies on this argument to instead focus its resources into correcting launch related problems. In weighing the cost effectiveness versus the probability of collision, they find the effort to deal with space debris as not being worth it. Again, from

a historical view, this may be correct. However, the rationale behind the argument is flawed and very short-sighted. Conceivably, it could be too late to take action once space debris failures overcome launch rate failures.

4. The Driving Force: Space Station

So, why is space debris of such concern now? The truth to this question may include several possibilities. However, the one, single event that has caused this issue to come to light so quickly has undoubtedly been the construction of the international Space Station. The largest undertaking since the Apollo missions, the Space Station is mankind's next stepping stone into space.

With the advent of the Space Station, space debris has come under greater scrutiny. Once constructed, the Space Station will orbit the Earth at an altitude of approximately 400 km and an inclination of 28.5 degrees. Concern for the Space Station is valid: the orbital debris environment in LEO presents a problem even now for space operations which involve large spacecraft or satellites in orbit for long periods of time [Ref. 3, p. 14]. At its proposed position, the Space Station will be in an area of great concern. In order to cope with this environment, it will be necessary to shield it over large areas in order to achieve the required design safety criteria.

C. SUMMARY

From the information and perspectives gleamed from above, some truths are starting to emerge. First, LEO is the worst orbit both in terms of debris distribution and population density. Also, when compared with GEO, higher velocities occur at these lower altitudes which in turn can cause larger impacts and subsequent satellite fragmentations. Next, less is known about GEO than LEO; this is due primarily to limited data gathering capabilities. However, what is known, from both orbits, is inaccurate to a certain degree. Lastly, and most importantly, the issue of space debris is a growing one; Figure 35 shows a historical increase in the number of objects in orbit, by size, over time. Present day practices and applications will exacerbate the problem in

accordance with all accepted model predictions. It is this aspect of the issue which makes space debris such a grave problem and a looming threat. In closing, given the characteristics of the debris environment, it can be said that orbital debris is a potential threat to space activities.

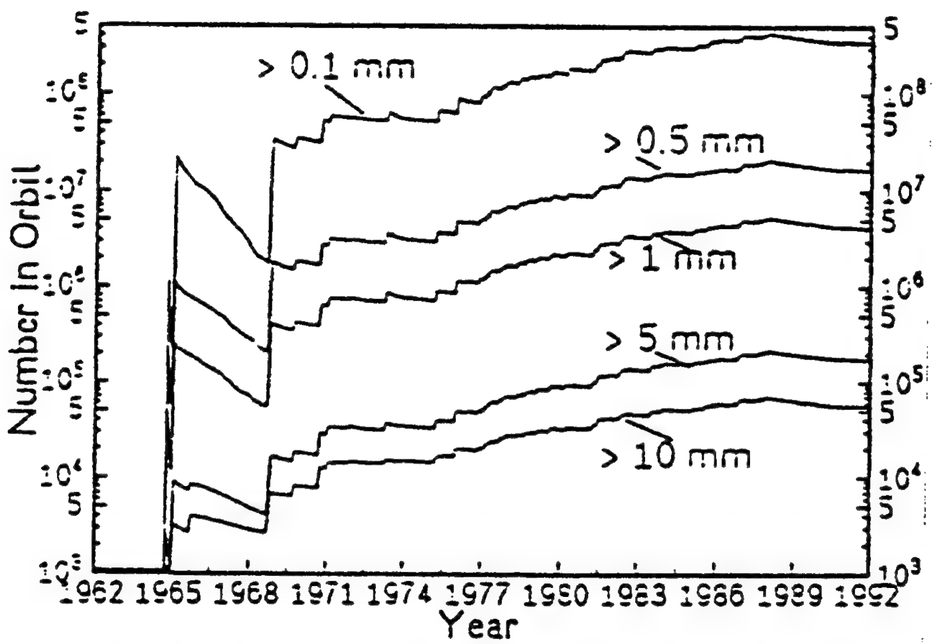


Figure 35. Number of Objects in Orbit vs. Time. [Ref. 2, p. 347]

III. ADDRESSING THE PROBLEM

This chapter illustrates the current efforts regarding the space debris issue. As a result of the overwhelming evidence concerning the growing threat of space debris, all major space powers have established orbital debris research programs. The cornerstones of ongoing programs are highlighted herewith.

A. POLICY AND LEGAL ISSUES

To date, no international treaty or law regulates or constrains the creation of orbital debris. Most would argue that existing data on orbital debris are inadequate to support any definitive policy actions [Ref. 21, p. 408]. There are, however, two relevant UN sponsored space treaties in effect. They are known as the 1967 Outer Space Treaty and the 1972 Liability Convention. The 1967 Outer Space Treaty is a treaty on the principles governing the activities of states in the exploration and use of outer space, to include the moon and other celestial bodies. From this treaty, the articles of most concern, with regards to orbital debris, are articles VI, VII and IX. In accordance with S. Neil Hosenball, former NASA General Counsel, these three articles can be applied to the orbital debris problem. Article VI claims that treaty signatories bear international responsibility for their national space activities, whether sponsored by their own government or by members from their private sector. Article VII establishes the principle that a signatory that launches or procures a launch of an object into space is internationally liable for damage caused by that object to another signatory. Article IX calls for signatories to be guided by the principles of cooperation and mutual assistance. Mr. Hosenball believes that the phrase "potentially harmful interference" can be applied to orbital debris [Ref. 9, p. 15]. As for the 1972 Liability Convention, it focused on the international liability for damage caused by space objects. From our perspective, it

elaborated on Article VII from the 1967 treaty. Specifically, it defined space objects as including component parts of spacecraft, their launch vehicles, and component parts of their launch vehicles. However, the agreement has a major caveat when fault is established as the basis of liability for damage between space objects. It is only applicable if the identity of both objects are unambiguous. Despite their shortcomings, these international agreements remain the most pertinent to the orbital debris issue. However, these preliminary space laws are not directly applicable to the orbital debris problem and have not been used to control the growth of space debris.

1. International Consensus

Despite the lack of an internationally sponsored agreement on the space debris problem, there are several ongoing efforts by individual countries' space agencies. It appears that where international law efforts have failed, cooperative agreements among several state space agencies have succeeded. Through several informal, non-governmental meetings, these major space-faring organizations have focused on efforts to pursue an international code of conduct which helps to minimize the production of new debris. They accomplish this by concentrating on technical rather than regulatory issues, and by developing accepted debris mitigation practices. Through their efforts, the community's needs are better served than by current international law. These organizations realize that concerns are international in scope and actions to control the growth of debris must be taken now.

2. US

The US has taken the lead on the issuance of space debris policy. In 1988, President Reagan signed the National Space Policy. In it, he included a statement that "all space sectors will seek to minimize the creation of space debris. Design and operations of space tests, experiments and systems will strive to minimize or reduce accumulation of space debris consistent with mission requirements and cost effectiveness" [Ref. 3, p. 17]. In 1989, there was an addendum to the National Space Policy; it called for the US. government to encourage other space-faring nations to adopt

policies and practices aimed at debris minimization. This policy expands the 1987 DoD policy, discussed below, applying it not only to the national security sector but to civil space activities as well. With the exception of these two statements, no comprehensive national policy concerning orbital debris presently exists [Ref. 3, p. 17].

There are no comprehensive agency policies or commercial regulations considering orbital debris either. However, there are some limited policy statements and regulating mechanisms which address some debris considerations in both the commercial and government sectors of America's space program.

a. NASA

NASA is at the vanguard of the orbital debris issue. What little has been accomplished to establish international debris minimization techniques or raising the general public's awareness into the problem, has been a direct result of NASA's untiring efforts. Since 1981, it has taken concrete steps towards minimizing the creation of additional debris in space. Then, NASA established a ten year, three pronged strategy for addressing the orbital debris issue: a technical approach, a measurements approach and a policy approach. And, in 1982, it established a venting policy. Specifically, it called for the venting of Delta upper stages; by releasing unspent gases and propellants, a potential explosion is defused. Since then, no hypergolic, that is, the oxidizer and the fuel ignite upon contact, stages have inadvertently exploded in space. Also, during the same year, NASA sponsored the first ever NASA Workshop on orbital debris at Johnson Space Center. Aside from creating various recommendations regarding the debris issue, this workshop showed to the world that there was a community of interest in the orbital debris problem [Ref. 3, p. 18].

More recently, NASA has commenced to address the issue by working closely with the DoD. In 1990, the American Institute of Aeronautics and Astronautics (AIAA) sponsored a NASA/DoD orbital debris conference in Baltimore. Again, several papers were presented highlighting the need to address the debris situation [Ref. 9, p. 65]. In the same year, NASA and DoD began joint orbital debris studies as stipulated by the

Interagency Group (Space) report from 1989. The goal was to characterize the LEO debris environment down to 1 cm and to identify candidate technologies for minimizing debris production and enhancing spacecraft survivability. They also began work on a guide for spacecraft builders and launch operators, tentatively titled, Space Debris Minimization and Mitigation Handbook [Ref. 3].

In summary, NASA's policy to limit orbital debris generation grew out of the Presidential directive in 1988. Currently, a handbook is being developed to support NASA Management Instruction (NMI) 1700.8, which is a general policy statement limiting the generation of orbital debris. This handbook defines design and operations techniques for limiting the generation of debris, provides support to help developing programs establish conformance to the policy, and supports the assessment of effectiveness of debris mitigation procedures [Ref. 22, p. 1].

b. DoD

DoD is an emerging advocate of the growing dangers of orbital debris. Presently, DoD's space policy supports and amplifies US national space policy. To this effect, DoD has taken several steps towards addressing the debris issue.

In 1987, DoD issued its first official orbital debris policy. It states that "DoD will seek to minimize the impact of space debris on its military operations. Design and operations of DoD space tests, experiments and systems will strive to minimize or reduce accumulation of space debris consistent with mission requirements." [Ref. 9, p. 53] By all accounts, this policy broke new ground because it specifically identified space debris as a planning factor in future military space operations.

Component services have also implemented guidance concerning space debris. In 1991, USSPACECOM issued regulation 57-2, Minimization and Mitigation of Space Debris; it delineates responsibilities and lists guidelines for the operation and development of current and future space systems with regards to space debris mitigation activities. [Ref. 23, p. 1] From another perspective, Air Force regulation SDR 55-1

directs program directors and managers to adjust satellite development and deployment plans to avoid orbital positioning problems [Ref. 3, p. 18].

Ongoing research efforts are also a major portion of DoD space debris policy. In response to the Interagency Group report of 1989, DoD has established a two phased Space Debris Research Program. As of October 1991, participants in the program included the Air Force Space Command, Air Force Systems Command, the Strategic Defense Initiative Organization, and the Defense Nuclear Agency. Phase I, a near term plan for FY 90-92, included goals such as the assessment of the orbital debris environment, development of Space Station Freedom design criteria, documentation of debris minimization procedures and practices, provision of design concept studies and tool development for spacecraft debris survivability, and continued support for the development of standards, national policy, and international agreements. Phase II, the long term portion of the program, encompasses FY 93 and on. Its main objective is to implement improvements, procedures and practices required to meet user needs. Although the program is making considerable headway [Ref. 4], some issues and concerns have been highlighted. Of most importance is the fact that there is no formally assigned DoD lead agency in the program; the Air Force is acting as a "de facto" leader. This limits the ability to provide overall program coordination, speak with one voice, and avoid duplication of efforts.

3. Other Space Organizations

Other state space agencies have followed in the wake of NASA's lead. Two of the foremost contributors to research into the space debris predicament are highlighted. Their driving concern: the problem cannot be resolved without international unity and cooperation.

As previously mentioned, technical experts are developing methods for reducing the quantity of space debris and advocating voluntary restraint rather than legal regulation. States involved in the use and exploration of outer space are developing policies to address the question of space debris management. These organizations are

also studying the technical, economic, legal and policy aspects of space debris [Ref. 25, p. 1].

a. European Space Agency (ESA)

Europe's concern with the orbital debris issue is highlighted in a paper presented by various international scientists at the World Space Congress held from 28 August through 5 September 1992 in Washington, D.C. It agreed on six major actions to be taken by the international community at large: the underlying theme to all was an urgent need to act now and the incorporation of mitigation practices [Ref. 26].

Through similar efforts, ESA is assuming a major role in the quest for international recognition and commitment to debris awareness and mitigation practices. Since 1986, with the creation of the Space Debris Working Group (SDWG), ESA began the assessment of the various issues of space debris. From SDWG recommendations, ESA's council formulated and adopted a policy on space debris with the objectives of minimizing the creation of space debris. It also approved a plan of activities [Ref. 2, p. 27]. The main element of the ongoing research activities is the Space Debris Research Program. Similar to the DoD Research program, it looks to study critical areas of the space debris issue and carry out preparations for future programs in a two phased plan. ESA's plan to cope with the debris problem relies heavily on international cooperation. They believe that space debris is a global problem which can only be solved by a joint effort, discussions and cooperation with other space agencies and related organizations must be further enhanced [Ref. 2, p. 31].

b. National Space Development Agency of Japan (NASDA)

By their own accounts, NASDA's orbital debris achievements are still very limited compared with those of the USA and Europe [Ref. 9, p. 79]. However, as an emerging space power, their efforts and commitment to the issue are well founded.

As with most other countries, no national guidelines on the issue have been formulated [Ref. 27, p. 1]. In light of this situation, and partly due to NASA's initiatives,

they too have founded a Space Debris Study Group. The objectives of the group are to promote overall space debris related research, to stimulate public awareness of this issue, and to provide guidelines to cope with it. Actual changes in policy have taken effect within NASDA as a result of the group's recommendations and other sources. It has implemented blow down and depletion burn of residual propellant of H-1 second stage, residual pressure in helium bottles and gas jet residual propellant [Ref. 27, p. 6].

NASDA's efforts are to be commended. Their early incorporation of space debris research into their overall space effort reflects highly on their commitment as a responsible space user. All this, despite no Japanese space projects being known to have created a large amount of debris.

4. Summary

The international space community is taking positive steps regarding the space debris problem in the absence of any international law or treaty. Through their collective, responsible efforts, the threat of space debris is being marginally addressed. In April of 1993, the four major space powers - ESA, NASDA, NASA and the Russian Space Agency (RKA) - met in Darmstadt, Germany for multi-lateral talks on space debris. The four agencies decided on formal terms of reference and a working group structure. They agreed to exchange technical information and experience in the context of a Space Debris Coordination Committee. To most in the orbital debris community, this gathering is the culmination of consciousness-raising activities in the international arena [Ref. 9, p. 93].

Despite these accomplishments, several issues of a legal nature remain unresolved; particularly anything having to do with the legal definition of space debris, a state's responsibilities and liabilities involving space debris, and just compensation in the event of a debris collision with an active satellite. Presently, these issues have not been addressed on a global level [Ref. 2, p. 683].

B. MODELING

Modeling of the space debris problem is another yardstick by which to measure the commitment of international space agencies to the issue of orbital debris. In the context of the debris issue, orbital debris modeling is a cornerstone to any space agency's debris research effort. Modeling activities are generally concerned with interpreting what can be directly measured in terms of what one would like to know. They are required both to fill in the gaps in the data and to project the future situation.

Modeling for the space debris issue can be summarized into three general categories: support models, evolutionary models and engineering models. Support models address specific problems such as orbit lifetime and debris stability. They apply environment models and measurements to specific problems such as debris environment characterization related to penetrability and predicting debris detection rates. Examples of this type of modeling include breakup models, orbit lifetime models, area-to-mass models, critical density models, LDEF related models, traffic models, flux models and flux directionality models. Evolutionary models are those that model a system through evolutionary scenarios. The model allows for a simple treatment of the gross features of environment evolution yet is consistent with expectations based on physical arguments. NASA's EVOLVE model is an example of an evolutionary model. Lastly, engineering models are those that incorporate results from models and measurements to produce a description of the environment which can be used by spacecraft designers [Ref. 28].

1. Orbital Debris Modeling

Orbital debris modeling is necessary because detailed knowledge of all man-made space objects has become important for present and future spaceflight. It is essential to know their size and mass distribution, and their altitude and inclination distribution in order to assess the collision risk for any new launch, to design shielding against the small particle flux and to study the feasibility of collision avoidance maneuvers [Ref. 12, p. 81].

There is an extensive orbital debris environment modeling activity supported by NASA/JSC; Figure 36 illustrates ongoing orbital debris modeling efforts. Initially, no models existed and most of NASA's orbital debris funding was directed towards the development of a modeling capability. Now, orbital debris models are being used to routinely support NASA's activities and programs. For instance, NASA's EVOLVE program is a detailed environment evolution model currently applied to LEO. It uses breakup models to determine the distribution of fragmentation debris created by collisions and explosions, and it uses historical records of launch traffic and mission models for future launch traffic as input data. It defines the debris environment as a time varying ensemble of objects in specific orbits. This particular model has been checked by comparing its results with observed environment characteristics. This is important, since a model can only be considered as accurate as when validated against measured data [Ref. 2].

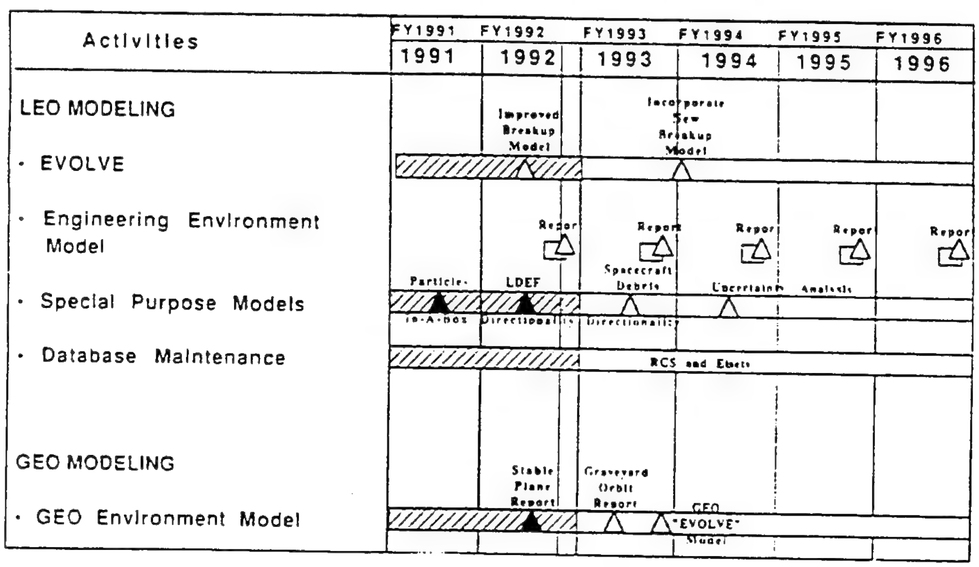


Figure 36. Orbital Debris Modeling in NASA. [Ref. 2, p.8]

2. Accuracy of Models: Validation

If perfect means of detection and tracking for space debris objects existed, mathematical models of the debris population would be unnecessary. However, as will be discussed later, this is not the case. Thus, models will always be necessary because measured data is incomplete and will always be incomplete; and because if only measured data of all orbital debris objects were available, it would represent only the current situation. There would be no room for simulations and future projections under various scenarios. Given the overall importance of models, models of an environment or a process must be tested empirically for accuracy and predictability. Most environmental models are validated against the Haystack radar observations or the USSPACECOM catalog.

From our example, EVOLVE's comparison with the USSPACECOM catalog has indicated that the debris environment is being modeled well to debris sizes of 10 cm and larger; however, EVOLVE has more debris in the size range of 10 cm to 1 meter (m) than the catalog. When compared with Haystack data, it was found that the debris environment model needs to be improved for debris to sizes as small as 1 cm.

Despite these validations, there will always be a degree of uncertainty associated with all models. For instance, there is a significant amount of uncertainty with current debris environment as determined by NASA/JSC. See Figure 37. At 400 km, the flux for particles below 1 cm have uncertainties well over an order of magnitude [Ref. 6, p. 146].

3. Summary

All of the major space powers have established orbital debris modeling activities into their space debris research programs. Their collective objectives in developing these models are to insure continued support of orbital debris related activities and major agency programs, and to improve the fidelity of existing models by incorporating new environmental data.

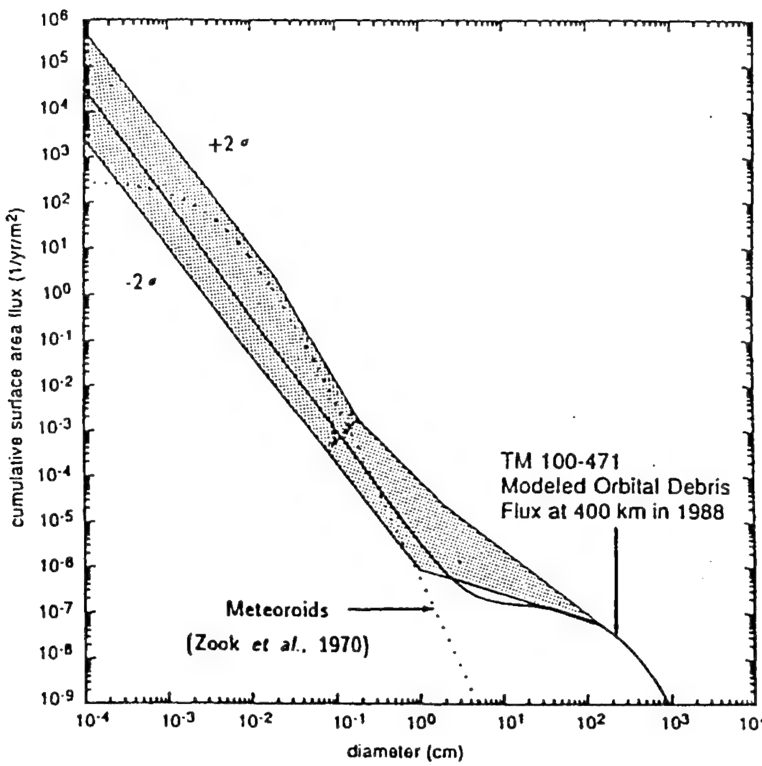


Figure 37. Uncertainty in Current Environment at 400km Compared to NASA's TM 100-471 Model. [Ref. 6, p. 146]

As with any modeling attempt, certain baseline assumptions have been made with most orbital debris models: assumptions have been made concerning debris source and solar activity. Uncertainties in all models derive from observational limitations, unmodeled sources, and unpredictable solar activity [Ref. 3, p. 11].

C. MEASUREMENT

Monitoring of the space debris environment is an important facet to any debris research program. Measurement of the debris environment can be made by either direct or indirect methods; that is, through observation using radar and optical systems, or through the analysis of returned space objects. Since no foreign country, with the

exception of the former Soviet Union, has a major capability for tracking satellites and orbital debris, measurement efforts will focus primarily on US capabilities. Figure 38 summarizes ongoing and projected orbital debris measurement undertakings.

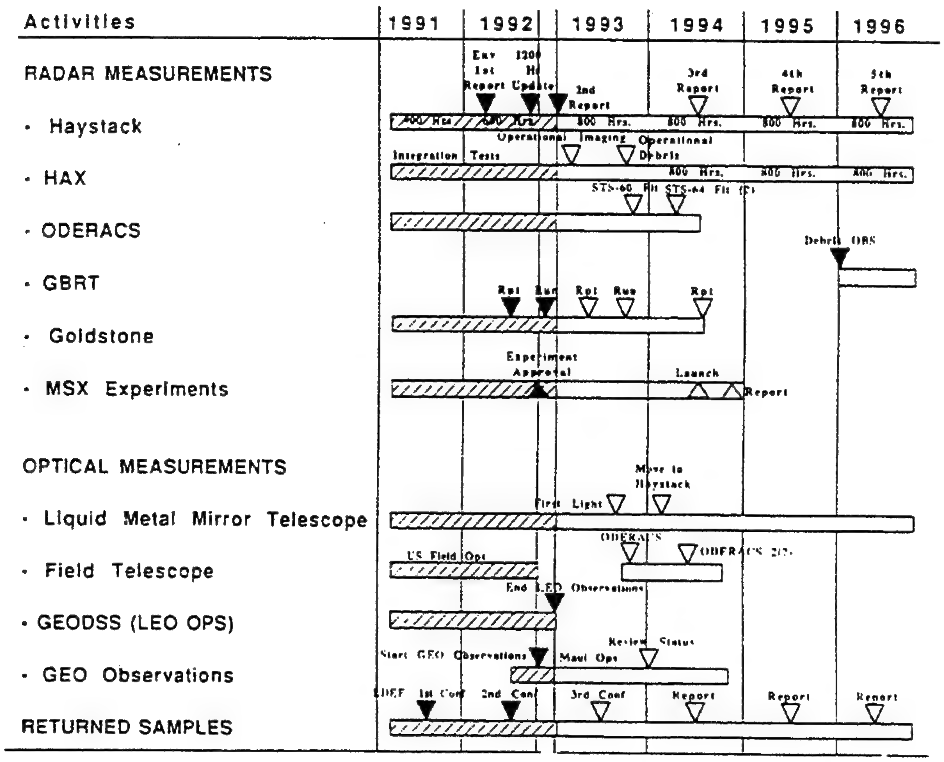


Figure 38. Ongoing and Proposed NASA Measurement Activities. [Ref. 2, p. 9]

1. Maintaining a Catalog

The primary data source for analyses of the measured Earth satellite population is the USSPACECOM's satellite catalog. Within the US, the Space Surveillance Network (SSN), operated primarily by DoD, is tasked to monitor man-made objects in space. Initially, the primary reason for having established USSPACECOM's space surveillance and tracking mission was for it to be able to distinguish between benign satellites and incoming ballistic missiles. Given the current debris situation, this simple task has turned into an enormous effort. Every day over 40,000 individual observations are made by

USSPACECOM using both a space-based constellation of geosynchronous launch detection sensors and a ground-based network of sensors. However, these space-based sensors provide no observation for space surveillance; they focus on data collection of launches. Each observation is forwarded to USSPACECOM's Space Surveillance Center (SSC) in Cheyenne Mountain, Colorado. There, the observations are checked against the entire satellite catalog to determine if each represents a known or an unknown object.

This satellite catalog is the most important tool for space surveillance; it is essential to space control operations. The catalog enables USSPACECOM to predict possible collisions between satellites in Earth orbit. It also allows the command to predict when objects will start to reenter the Earth's atmosphere. In general, the catalog is maintained via the SSC. The SSC tasks the SSN to use the satellite catalog to track satellites; the SSC then takes the observations and updates the satellite catalog.

The satellite catalog includes a database that is used to chart the current position of Earth orbiting satellites and predict their future orbit paths. The catalog dates from 1957, when Sputnik was launched. The catalog contains two types of information: administrative data and orbital parameter information [Ref. 12, p. 220].

Sensors that support the space surveillance mission are located around the world. Today, some twenty six sensor systems make up the USSPACECOM SSN; refer to Figure 39. Presently, USSPACECOM is not required to track and maintain orbit predictions on small debris; that is, on objects less than 10 cm. According to a recent study, if the SSN were to be tasked to track objects smaller than 10 cm, more sensors, communications lines and computers would be required [Ref. 12, p. 226].

2. Surface Capabilities

a. General

The network used by the SSC uses several types of sensors including mechanical tracking radar, tracking telescopes and phased array radar. Table 2 lists available ground-based sensors and their characteristics [Ref. 12, p. 225]. The capability of sensors to track is a fixed function of their total sensor tracking opportunities. It

should be noted that most of the sensors indicated are corollary or collateral assets and not dedicated to space surveillance. Only the facilities at Eglin Air Force Base, FL and NAVSPASUR are dedicated to space surveillance; the others are tasked on an "as needed" basis [Ref. 30, p.1].

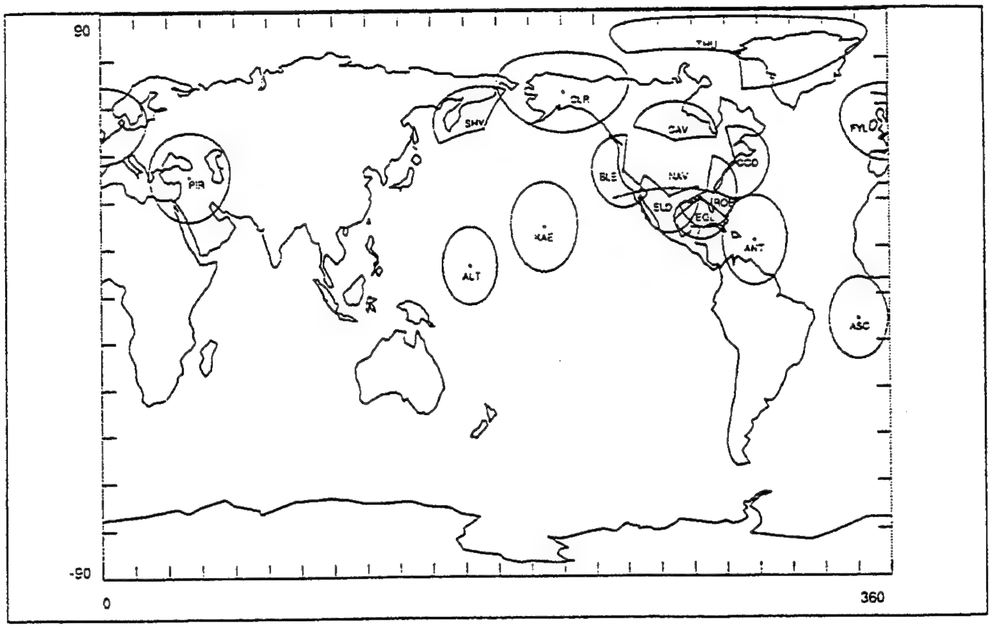


Figure 39. World Locations of SSN Sensors. [Ref. 29]

USSPACECOM has three component commands: Army Space Command (USARSPACE), Naval Space Command (NAVSPACECOM) and Air Force Space Command (AFSPACECOM). Each component contributes organic assets in order to accomplish USSPACECOM's mission. USARSPACE provides support through two space surveillance sensors contributing to the USSPACECOM satellite catalog. These sensors are called ARPA-Lincoln Tracking and Identification Radar (ALTAIR) and the ARPA-Lincoln Coherent Observables Radar (ALCOR). NAVSPACECOM's contribution includes sensors from the oldest space surveillance system still in use, the

Naval Space Surveillance System (NAVSPASUR) Fence. This sensor creates an electronic barrier across the southern US. at approximately 33 degrees north latitude. Its three transmitters and six receivers provide coverage to an altitude of 15,000 nautical miles (27,780 Km). Finally, AFSPACECOM provides twenty-five worldwide sites to USSPACECOM to support space surveillance [Ref. 12, p. 218].

TABLE 2. SSN SENSOR CAPABILITIES. [REF. 12, P. 225]

SYSTEM	LOCATION	SENSOR TYPE	RANGE (km)	SMALL DEBRIS CAPABILITIES
		RADAR		
ALCOR	Kwajalein Atoll	C Band	5,555 km	
ALTAIR	Kwajalein Atoll	UHF/VHF	40,000 km	
FPQ-14	Antiqua Ils	C Band	2,300 km	
FPQ-15	Ascension Ils	C Band	1,600 km	
FPS-92	Clear, AK	UFH	5,555 km	
HAYSTACK	Millstone Hill, MA	X Band	35,000 km	
COBRA DANE	Shemya Ils	L Band	5,555 km	
FPS-85	Eglin, Fl	UHF		**
FPS-49	Fylingdales, England	UHF	5,555 km	
NAVSPASUR	Dahlgren, VA	Continuous Wave	8,100 km	
FPQ-14	Kaena Point, HI	C Band	1,800 km	
MILLSTONE	Millstone Hill, MA	L Band	35,000 km	
FPS-79	Pirinclik, Turkey	UHF	4,300 km	
PAVE PAWS	Cape Cod, MA Beale, CA Robins, GA Eldorado, TX	UHF	5,555 km	
		Electro-Optical		
AMOS	Maui, HI	Visible, LWIR	35,000 km	
GEODSS	Socorro. NM Taegu, Korea Maui, HI Diego Garcia	Visible	35,000 km	**
MOTIF	Maui, HI	Visible, LWIR	35,000 km	
SITU	St Margarets, Canada	Visible	35,000 km	

There are several types of radar in use by USSPACECOM. For instance, mechanical tracking radars generally have only one tracking beam. These types of radar do not have the means to track objects smaller than 10 cm. Additionally, these radars do not have time to track objects such as small debris; they are used primarily to track large objects such as rocket bodies and active payloads. There are also tracking telescopes available. These telescopes also have a single object tracking capability. Depending on atmospheric conditions and visibility, they are capable of tracking small debris. But, similar to mechanical tracking radar, these telescopes are used primarily for other tracking missions and have no time for small debris. Lastly, there are phased array radar which can functionally use more than one tracking beam and can therefore track more objects simultaneously. Only a few of these radar have the inherent capability of tracking small debris less than 10 cm in size. Sensors that could support this type of tasking are those found at Cavalier and Eglin.

There has been much concern recently over the limitations of the sensors used by USSPACECOM. Given the threat and predicted populations of debris objects of 10 cm or less, these shortcomings may prove disastrous. As one USSPACECOM official put it: "Bottom line is this. If the catalog doubles, there are few sensors that have available tracking opportunities to handle this. One would expect that the phased arrays of the existing SSC network should be able to handle it. However, if the catalog increases on the order of tenfold, then new tracking sensors will probably be required" [Ref. 12, p. 224].

Figure 40 shows USSPACECOM's tracking capabilities and highlights the resolutions at different altitudes. From this figure, one can see that any object smaller than 8 cm cannot be reliably tracked by the SSN; the smallest fragment that can be measured at altitudes greater than 1000 km is approximately 10 cm in diameter. Partial reason for this limitation is due to the resolution capabilities of SSN radar, as shown in Figure 41. Since no object can be catalogued unless two or more sensors track an object, the overall capability of the network is less than their best radar.

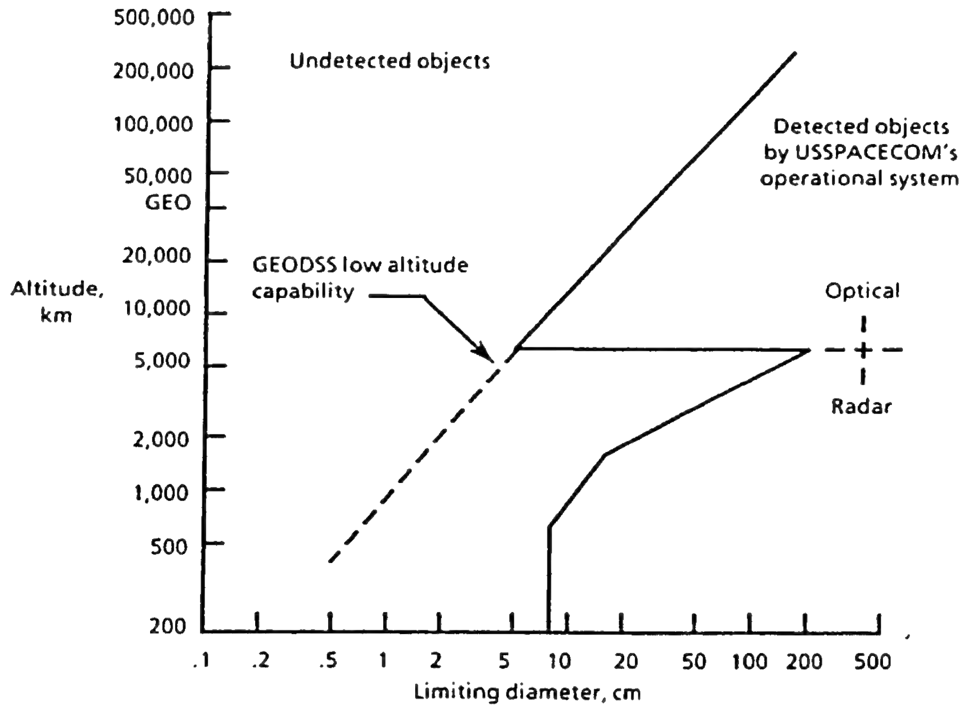


Figure 40. Sensor Limitations Diagram. [Ref. 31, p. 6-1]

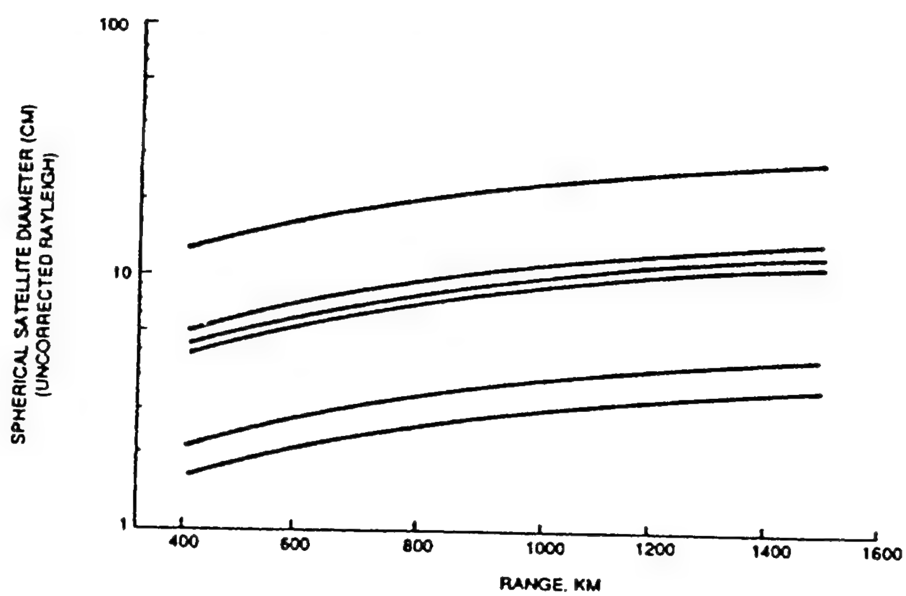


Figure 41. Sensor Resolution. [Ref. 1, p. 28]

There are other means of procuring accurate data through sensors outside the USSPACECOM network. Unlike the sensors in the SSN, these sensors were not built with another task in mind. That is, most SSN sensors were not designed to track small debris; they were built to track large, metallic ballistic missiles. Several proposals have been put forth by the international space community. For instance, from the Netherlands, the thought of using the Infrared Astronomical Satellite IRAS to perform a sky survey at 10 to 100 um wavelengths has been proposed. Radar measurements of small debris has also been proposed by using the Arecibo and Goldstone radar. Lastly, the Mu radar, a high powered VHF Doppler radar, from Japan has been considered to conduct orbital debris measurements. The majority of these newer radars are better equipped to handle the smaller radar cross sectional area presented by small debris sizes [Ref. 12, p. 245-263].

b. Increasing Current Capabilities

As we have seen, the radar frequencies and corresponding wavelengths required to accomplish the SSN's current mission are different than those required to efficiently detect smaller objects; as well as a sensor's beam width and power. To detect smaller objects, certain radar, would have to be significantly modified; a process that would make sensor's unavailable for their primary mission.

As the Intergroup Agency report on space debris pointed out, there exists much room for improvement. Several options are available to improve the detection, tracking and monitoring capabilities of the SSN. The technology exists to allow USSPACECOM to increase the number of objects which can be catalogued.

A combination of several approaches exist. These include modifications to existing ground-based sensors, development of space-based surveillance and new data management and data processing concepts. Recommendations include:

(1) Using the Debris Environment Characterization Radar (DECR). By using this narrow beam radar, the debris population in LEO could be physically defined.

(2) Increasing power on existing collateral radar. By increasing the power output of a radar, its detection capability will be consequently increased.

(3) Employing the MIT/Lincoln Laboratory small object identification. By using the Haystack radar, the same results obtained with a DECR could be produced.

(4) Use of the Reentering Debris Radar (REDRAD). This could be used to determine the rate of elimination of debris from the environment.

(5) Exploiting other domestic or foreign radar.

(6) Development of space-based debris radar.

(7) Expanding existing optical sensor capabilities [Ref. 3].

Unfortunately, most of these suggestions include a large price tag. Studies have concluded that improvement of existing sensors in order to track smaller sized debris is cost prohibitive. Currently there are no plans to upgrade any of the sensors within the SSN [Ref. 5].

3. Returned Material Analysis

In addition to ground and space-based sensors, opportunities for direct examination and analysis of surfaces exposed to the LEO debris environment have been possible upon their return from space. As a result of both active and passive in-situ experiments, retrieved material analysis from space provides additional insight into the debris environment. Spacecraft exposed to the LEO environment for a long period of time are more than likely to have encountered impacting meteoroid and debris particles. Evaluation of these hypervelocity impact features provide information on the size distribution, composition and source of smaller debris particles.

Currently, space debris particles smaller than a few millimeters cannot be detected using remote measurement techniques described above. The only method to accomplish this is with in-situ techniques. In all current systems, the extent of the environment measured and the statistical validity of the data obtained are both dependent on the total exposed area of a spacecraft. Until recently, all in-situ debris environment data were provided solely using passive techniques. In passive techniques, samples of

materials are exposed in space and then returned to Earth. There, the resulting craters or impacts are examined, measured and interpreted into particle diameters and impact velocities.

Two recent observations have arisen in two opportunities of major importance. These are the return of approximately 3 square meters of space-exposed surfaces from the repair of the Solar Max satellite after 4.15 years in space, and the January 1990 return of 130 square meters of exposed surface from the LDEF after 5.7 years in space. To a lesser degree, information concerning debris impacts is also obtained from returned shuttle flights. Although no intensive effort has been established to carefully study the Shuttle windows for debris impacts, they are examined after each flight for impacts and other damage that could compromise safety for the following mission.

The returned Solar Max satellite has been a major source of new data on the small debris and meteoroid population for sizes below 0.01 cm. After analysis, it was determined that the major source for these small particles result from the disintegration of painted surfaces of spacecraft and the firing of solid rocket motors in space [Ref. 2, p. 195].

The LDEF, the first active in-situ experiment, has also provided a unique opportunity for the in-situ study of the many processes involved with orbital debris and upon high velocity impacts of such. From the crater size distribution, a comprehensive description of the actual particulate LEO population has been possible. Also, the analysis of the morphology of individual impact craters on the surface provides a method for determination of the direction of the impacting particles. It was discovered that orbital debris were dominant on spacecraft surfaces facing the velocity vector [Ref. 2, p. 159].

D. SUMMARY

Often, the manner in which a person reacts speaks volumes. For instance, given a low threat situation, one is more than likely to ignore the problem and continue about

their routine business. However, the same cannot be said given a high threat condition: a person will act differently because the threat is of larger concern to their well-being.

In continuing this analogy, the same can be said of orbital debris. How the world and the scientific community react tells one that orbital debris is indeed a matter of grave concern. The ongoing efforts and activities in the policy, technical, and measurement aspects of space debris research clearly support this position. Orbital debris is a new reality facing all space faring nations; it is a threat of great concern to the collective well-being of the international space community.

IV. SPACE DEBRIS STRATEGIES

The previous chapters have served to educate and heighten one's awareness concerning the space debris issue. By this time, the reader has more than likely realized that debris poses a threat to current and future space activities, and is of great concern to the space community. The reason it has become of great concern is because of the threat debris poses to the survivability of space assets. A solution to the debris problem is as complex as the problem itself. In order to be effective, strategies must be developed to simultaneously decrease the dangers of the debris environment and cope with the current threat that the environment poses to spacecraft. This chapter explores several methods for accomplishing this goal; it presents feasible solutions to the problem. These strategies focus on LEO techniques. Advantages and limitations of each approach are examined.

A. MINIMIZING DEBRIS GENERATION

The practice of minimizing debris generation is a crucial step to controlling the debris environment. There are options available to control, limit, or reduce the growth of orbital debris. However, none of them can significantly modify the current debris environment. They can only influence the future condition of the environment.

We have seen that man-made debris represents a collision hazard to active satellites. Small, untrackable particles can collide with spacecraft at hyper-velocities and cause catastrophic damage. The probability of a collision between large objects, 1 m or larger, is very low [Ref. 12, p. 180]. But, collisions between small particles and large particles are more likely and the source of a growing debris population. Also, it has been presented that, a steady increase of the number of objects in LEO will always lead to a chain reaction of collisions. If spaceflight activities are continued as in the past, the critical population mentioned by Dr. Kessler could be reached within the next few

decades. Thus, in any event, the Earth orbiting population must be limited in any case, because a steady increase will lead to worsening conditions.

The control of orbital debris can be approached as a problem of either correction or prevention. Corrective approaches include efforts to retrieve derelict spacecraft and sweeper devices to remove small debris. Preventive measures call for provisions for self-removal of spacecraft and rocket bodies, and the increased use of reusable space hardware. Furthermore, three generic options of debris control can be identified: mitigation options, disposal or elimination of orbital debris objects, and active removal or cleaning activities.

1. Current Trends

Most current trends focus on limited mitigation practices and some disposal efforts through de-orbiting.

a. Design Procedures

Presently, current hardware and ongoing activities have occasionally been modified for debris prevention. A few design efforts, however, have included debris-prevention objectives from the start. Three to be exact. These are the Space Station, RADARSAT and IRIDIUM.

Not only has the Space Station design team been looking at options to prevent the creation of orbital debris, but also at methods to protect the station from debris and to avoid contamination of the surrounding environment. RADARSAT, a Canadian remote sensing satellite in a polar LEO, is another example of the incorporation of debris environment considerations into the overall design philosophy of a satellite. Among other activities, to be discussed later, RADARSAT considered several mitigation options. It considered de-orbiting the satellite after its useful life, and adhered to the practice that there would be no hardware items cast loose into space during either the spacecraft separation or release of its extendible Small Aperture radar and solar arrays [Ref. 32, p. 17]. Lastly, IRIDIUM, one of several proposed LEO communications constellations with worldwide coverage, is one of the first to implement a comprehensive program for debris

mitigation. It will be implemented during the design phase and will be continued through the operations phase. Highlights of their efforts include selection of orbits to decrease collision hazards, de-orbiting of their spent spacecraft and minimizing debris associated with insertion and deployment. These three examples illustrate the commitment to debris mitigation practices. They also highlight another characteristic associated with mitigation activities; that is, implementation of mitigation practices must occur at the earliest phases of a program.

b. Operational Procedures

Some operational procedures have already been adopted by various agencies in order to minimize debris generation. Interestingly, these procedures have occurred on an ad-hoc basis and were not due to any formal international agreement. Operational procedures to reduce the growth of debris occur via several different methods and practices. Generally, they fall into one of two categories: those associated with mission operations, and testing operations in space.

Debris mitigation practices have been incorporated in mission operations for both launch vehicles and for payloads. To avoid spontaneous explosions, upper stage modifications have been made to existing rockets; such as the US Delta, the Japanese H-1, and the European Ariane rockets. In June of 1993, the Chinese Launch Vehicle System Design and Research Institute announced that the upper stage of the Long March 4 rocket is being redesigned to make it less likely to explode in orbit. Additionally, venting procedures have been incorporated into some space agency operating procedures. By venting the oxidizer remaining in the stage after it reaches its intended orbit, inadvertent explosions can be prevented. Other examples of mitigation practices, particularly from NASA, include pre-launch and on-orbit planning considerations; Collision Avoidance on Launch (COLA) and Computation of Miss Between Orbits (COMBO) programs are routinely accomplished for each Shuttle mission.

Similar procedures have been adopted in testing efforts in space, primarily in military-related testing. Previously, testing was conducted without great concern to the

impact their actions caused to the space environment, such as with the Midas 4 satellite [Ref. 9, p. 4]. In 1961, the US Air Force deployed a spinning 35 kilogram canister into orbit at 3220 km in support of Project West Ford. The canister holds 350 million hair like copper dipole antennas, the West Ford Needles. They are meant to scatter along Midas 4's orbit, forming an 8 km wide by 40 km deep belt around the Earth. Other examples of this disregard have included past Anti-Satellite (ASAT) weapon testing. DoD has changed to some extent the manner in which they perform national defense related testing. Through their own past experience in creating space debris, DoD has acknowledged that accumulation of debris can be minimized through careful planning. This attitude seems to prevail to date. For instance, the Delta 180 SDI was planned in such a way as to ensure the least amount of debris proliferation. By conducting the test at a lower altitude, DoD assured that all test-related debris re-entered the Earth's atmosphere within 6 months [Ref. 3, p. 31].

Although most of these practices are voluntary and implemented in a decentralized and limited manner, these actions have already had a positive impact on the debris environment [Ref. 3, p. 31]. For instance, the rate of increase of orbital debris from US sources has dropped 15% because of the Delta modifications alone. Continued implementation of these practices can only suggest a lowering of the probability of collisional hazards and removal of additional debris sources. Figure 42 shows the effectiveness of preventive measures and of subsequent active removal of large objects from high altitudes [Ref. 2, p. 602].

2. Options for the Future

Figure 43 highlights ongoing orbital debris mitigation efforts. In discussing this section, future influence of the debris environment can be categorized into three generic option groups; they overlap and are similar to the current protective and corrective measures described above. These are described below.

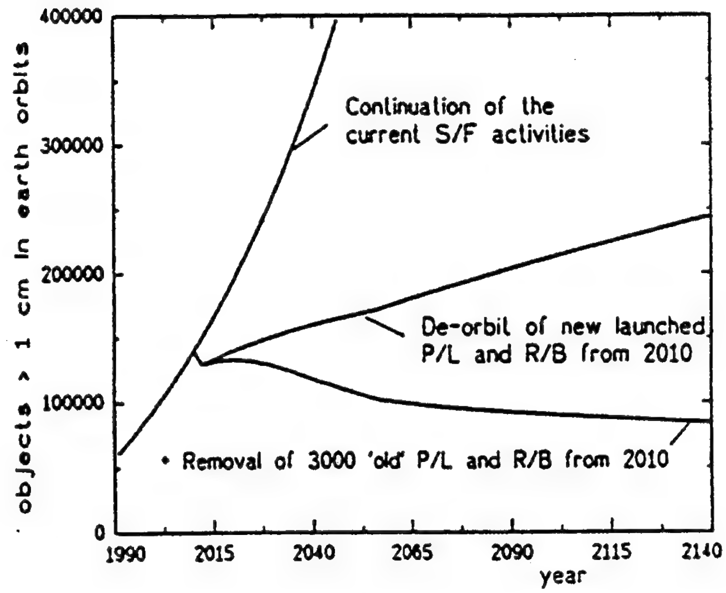


Figure 42. Effectiveness of Preventive Measures. [Ref. 2, p. 602]

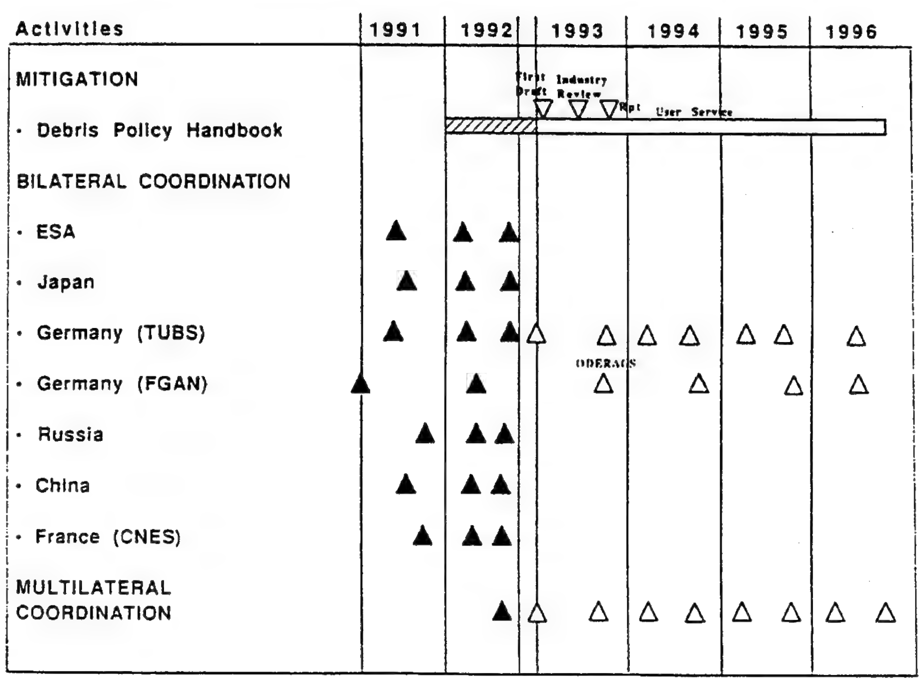


Figure 43. Orbital Debris Mitigation Effects Summary by NASA. [Ref. 2, p. 11]

a. Mitigation

Mitigation options include those measures such as booster and payload design, the prevention of spontaneous explosions of rocket bodies and spacecraft, and the research and application of "particle free" propellants.

Litter-free spacecraft operations could be achieved by combining design and operational practices. Launch vehicles and spacecraft can be designed to dispose of separation devices, payload shrouds and other expendable hardware at low enough altitudes and velocity so as not to become orbital. Also, stage separation devices and spacecraft protective devices such as lens covers can be kept captive to the stage or spacecraft with lanyards or other means in order to minimize debris.

When stages and spacecraft do not have the capability to de-orbit, they must be designed to become as inert as possible after their lifetime. Some of these measures have already been discussed, such as expelling all hypergolic propellants and pressurants; or insuring that batteries are protected from spontaneous explosions. Either effort would require modifications in design or operational practices, but could be achieved in order to limit further orbital debris created by any space operation.

Lastly, research into the possible use of particle free propellants is another option available. Elimination of particles from solid rocket motors can be accomplished; such a program already exists for tactical missile propellants. If aluminum oxide particles are removed from propellants, small debris would be greatly reduced. In closing, Figure 44 illustrates the effect of debris mitigation measures on the debris environment; clearly, mitigation efforts have a positive influence on debris population numbers.

b. Disposal

Disposal options for LEO include the elimination of orbital debris objects. This avenue of approach is more aggressive than mitigation practices because it removes large objects from the environment that can pose a potential hazard in the creation of new

debris. The largest drawback to this strategy is that it usually involves significant costs and is difficult to execute.

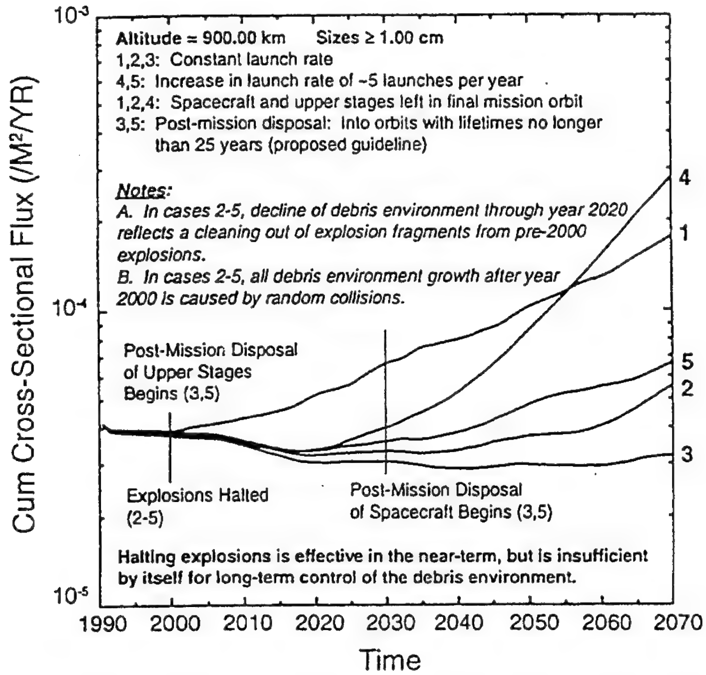


Figure 44. Effect of Debris Mitigation Measures on the Debris Environment. [Ref. 10]

Disposal practices can be incorporated into a spacecraft system in two general approaches: through mission design and through system configuration and operations. Mission design includes all those activities which dispose of debris through the careful design of the system's mission. However, these measures often have a significant performance penalty to both the launching craft and the satellite itself. For launch vehicles, this involves allowing sufficient propellant to remain in order to perform a controlled de-orbit burn. Or if the stage cannot inherently perform these maneuvers, it must be modified in order to accomplish this option. For satellites, disposal involves the same considerations; valuable fuel must be available to perform required de-orbiting maneuvers. Spacecraft mass penalty for providing de-orbit capabilities are shown in

Figure 45. One can see that the mass penalty continues to grow with increasing altitude but the slope becomes relatively flat beyond 10,000 km. The goal for the satellite is to achieve a re-entry into the Earth's atmosphere and be disposed of in the ocean [Ref. 12, p. 182]. A trash or disposal orbit is also a feasible solution. However, for LEO, this is not a good strategy because it requires a two-burn maneuver that is more fuel prohibitive than a single burn required for re-entry. In any event, disposal techniques provide a means of reducing potentially hazardous debris sources. However, systemic studies to determine what is the most cost-effective course of action, and what considerations dictate the optimization criteria for a particular project are required. Figure 46 shows the effect of disposal orbit lifetime on the debris environment.

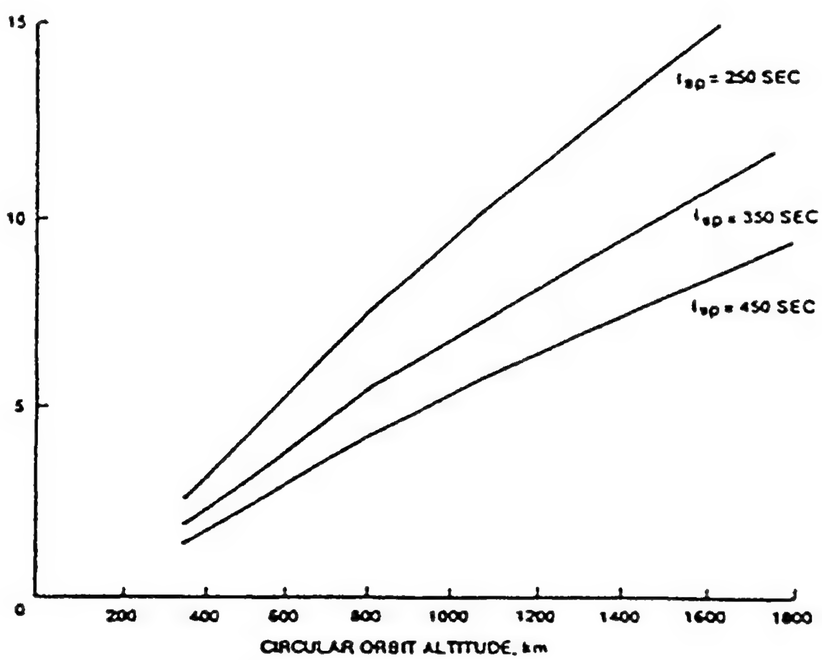


Figure 45. Mass Penalty Associated with De-Orbiting Operations. [Ref. 12, p. 182]

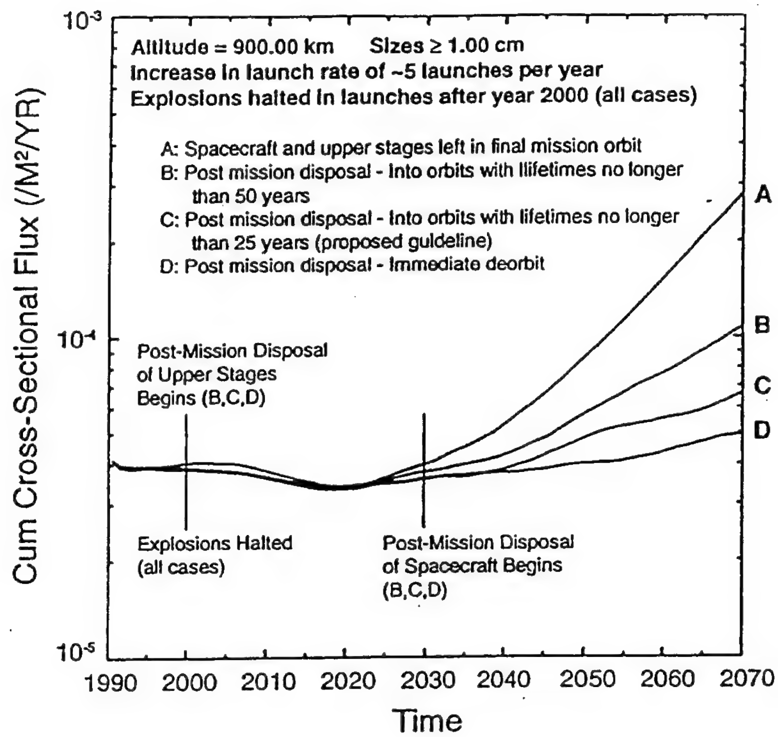


Figure 46. Environmental Projections for Post Mission Disposal Option. [Ref. 33]

When systems are not designed with disposal requirements, there are other alternatives available. These include looking at system configurations and operations; such as design modifications to current systems or design attributes for new systems. For LEO stages or spacecraft, it could be possible to maneuver to a lower perigee and employ a device to significantly increase drag. The effect of atmospheric drag on a satellite can be increased by deploying a large balloon which increases the effective area of the satellite without significantly increasing its mass. For objects orbiting below 800 km, a balloon with a diameter of 15 m can reduce the orbital lifetime of a satellite from several years to several weeks. Figure 47 shows orbital decay rates for spacecraft with and without various balloons attached. One of the advantages of drag device concepts is that the satellite does not need to maintain any specific orientation; no attitude control system is required. Drawbacks, however, to drag devices are that decreases in collision

probabilities due to shorter orbital lifetimes are offset by increased cross sectional area of the satellite. Similarly, studies and cost effectiveness assessments are required in order to maximize mission performance.

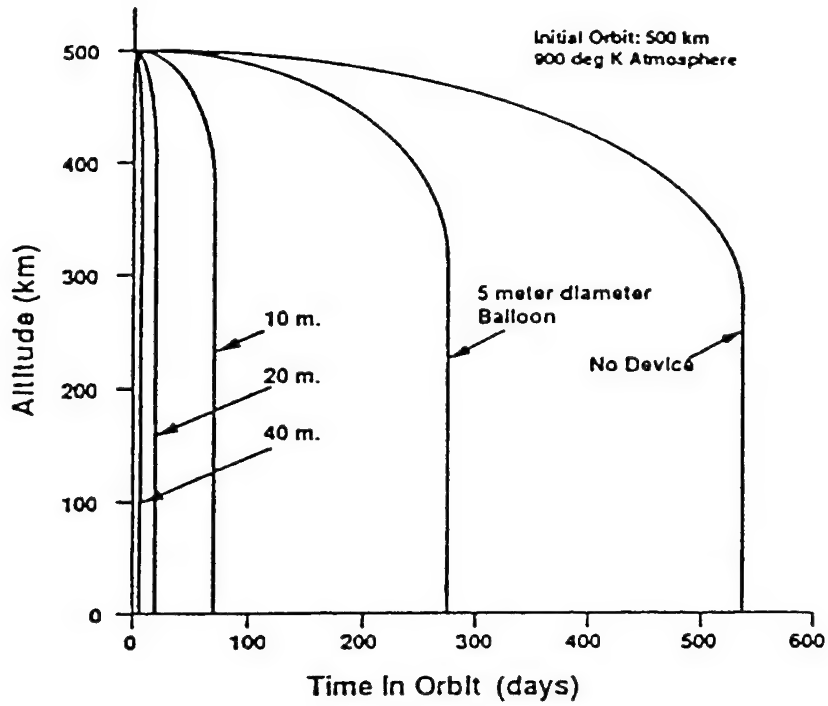


Figure 47. Orbit Decay Rates. [Ref. 12, p. 183]

c. *Removal*

Removal is as the name implies: it encompasses all means of active removal or "cleaning up" of the space debris environment by means of another system. Presently, the need for removal is only feasible, in terms of cost effectiveness, to LEO.

Removing large, inert objects requires some type of maneuverable system. This system must be able to rendezvous with the object to be removed and grapple onto it. To date, STS missions have proven capable of performing this activity at low altitudes and inclinations; but no unmanned system has these capabilities for higher altitudes and

inclinations. Conceptual studies indicate that these types of missions could be conducted with further analysis and development of new autonomous or remotely controlled removal systems; such as the Orbital Maneuvering Vehicle (OMV) under development by NASA. An OMV has several methods for removal of an object. First, it can perform a de-orbit maneuver, separate from the collected object and re-insert itself into orbit while the discarded object re-enters Earth. Next, the OMV and the collected object can remain together and maintained in a "safe" orbit for possible use as spare parts or raw materials. Another alternative is to rendezvous with an object and then attach a de-orbit device, such as a de-orbit propulsion kit or a drag inducing device. Lastly, the use of tethers could be employed in order to transfer moment between the OMV and the grappled object, thus lowering the orbit of the debris object and raising the orbit of the OMV. There are several concerns about using OMVs. First, there are legal and political limitations on the retrieval of space objects. Also, objects may be difficult to attach to if they are uncooperative, such as spinning or tumbling. Or, mission time required for orbit phasing and rendezvous could overtax the power supply of an OMV [Ref. 12, p. 180]. In the end, the cost is prohibitive; in LEO, an OMV could probably rendezvous with no more than two objects at a time.

As for the removal of small pieces of debris, currently no method exists. However, two strategies have been proposed: one is the use of active or passive devices to intercept particles with a medium, such as a large foam balloon, which absorbs the particles' kinetic energy. These 'debris sweepers' cause intercepted particles to decay more rapidly [Ref. 12, p. 184]. The other method calls for an active device to illuminate the particle with a directed energy beam causing the particle to either lose velocity or be broken into smaller fragments of less threatening mass and size. There are drawbacks to both proposals. The first system has a hard time differentiating between active and inactive objects; it could inflict damage on useful payloads. The other calls for elements that currently do not exist [Ref. 3, p. 34]. Figure 48 shows the theoretical benefits of subsequent active removal of small objects from the debris environment.

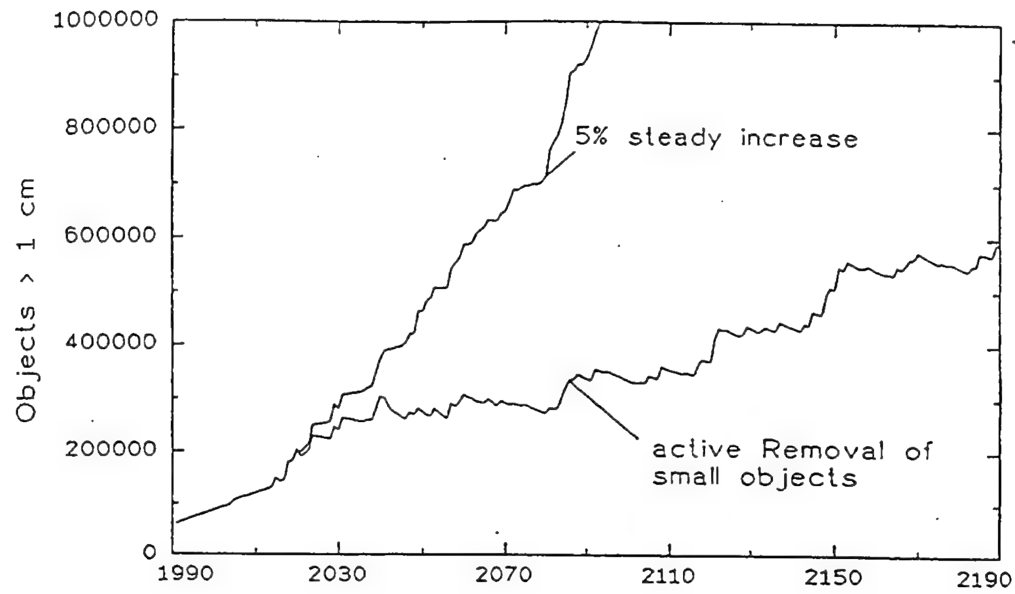


Figure 48. Effectiveness of Subsequent Active Removal of Small Objects [Ref. 3, p. 34]

The least cost effective manner for removing objects are those that are considered after the fact. They require adding new mass and systems into the environment, and their operations are difficult. While they are technically feasible, they are not viable candidates in terms of economic considerations [Ref. 2, p. 630].

d. Private Sector Recommendations

The space industry has suggested several varied proposals for coping with the debris issue. Some pertinent recommendations to this section are illustrated below.

Astro Innovations Inc. advocates change to international laws that would allow and encourage active salvage operations at GEO and GTO altitudes. The sovereign rights of space-faring nations could be maintained, while affording commercially attractive salvage opportunities to those so able.

General Research Corporation describes two orbital debris mitigation systems conceptually designed to be used in a variety of configurations to solve a number of debris related problems. The first system is a maneuverable free-flying spacecraft, and

the second is a shielding unit, or units, attached to the space system being protected. Grumman Space Systems proposes the use of their Tumbling Satellite Retrieval Kit in order to capture large pieces of orbital debris.

Finally, Kaman Sciences Corporation proposes a laser device that could be used to slow and de-orbit a variety of orbital debris. They claim that existing devices, experiments and analysis would permit rapid validation of this concept. All of these suggestions are in the conceptual phase and have yet to be validated [Ref. 3].

3. Summary

There are two points of concern: first, cost comparison studies at JSC, as well as common sense, have shown that current preventive measures are the best approach to controlling the growth of orbital debris [Ref. 12, p. 180]. Preventive measures are absolutely preferable to limit the population to an uncritical level. Subsequent active removal is always much more difficult, and more expensive. In other words, prevention is the best cure for the orbital debris problem. Second, in order to have a significant impact on minimizing debris generation it will require a concerted international effort.

B. ACTIVE DEBRIS PROTECTIVE MEASURES

In addition to the strategies presented above, two more general options are available in order to afford a spacecraft increased survivability in the LEO environment. Unlike the previous methods, collision avoidance and spacecraft shielding are reactive approaches to the debris threat and do not contribute to the mitigation of the debris issue. They directly affect the survivability aspect of a spacecraft through active means.

1. Collision Avoidance

The concept of collision avoidance, that is the act of avoiding a possible collision through pre-planned or evasive maneuvers, is at its earliest stages of employment. Collision avoidance can be implemented at either the pre-launch or during on-orbit phases of a mission. Although theoretically possible, actual implementation is difficult with current assets available in order to conduct collision avoidance. This is

because active maneuvers cannot be based on statistical methods. A prediction of an upcoming collision requires that an object endangering the spacecraft be detected in advance and specific information on its orbit become available. Active collision avoidance of all space objects is not presently practiced. There are limited cases, however, of some collision avoidance activities.

Pre-launch collision avoidance measures are feasible with existing tracking sensors. These activities include delaying launch times in order to avoid a passing system overhead. For instance, GOES 5 was delayed 36 seconds in order to avoid the passing Salyut 6 space station [Ref. 34, p. 2]. There is also the concept of employing traffic separation. This type of avoidance collision measure, similar to disposal orbits for inactive satellites, must be carefully considered during the earliest phases of a system's development. It calls for identifying orbits that are frequently used versus those which are of marginal importance or unused. Traffic separation would keep only active satellites in active orbital altitude belts. Use of such guidelines are the exception rather than the rule.

There are more collision avoidance measures ongoing in the on-orbit phase of a system's deployment. While in orbit, avoidance of particles of 1cm diameter is desirable. Presently, warning can only be provided by the existing SSN. However, the existing SSN can provide COMBO, collision or miss between orbits, only for objects larger than 10cm, but with an uncertainty in position to 1km above, below and across track and 2.5 km along track. As will be discussed below, it is feasible to shield against objects approximately 1cm or slightly larger, but the mass penalty grows rapidly with the size of the impactor to be defended against.

USSPACECOM currently provides safe times for launch to various customers, such as NASA and Global Positioning System (GPS)/Communications Satellites (COMSATS); adherence to their advice is strictly voluntary in nature. More extensive support is provided to ongoing STS missions. Their support is two faceted: support includes pre-launch collision avoidance and on-orbit collision avoidance. Pre-launch

support is similar to that discussed above. On-orbit support consists of constant analysis of the Shuttle's on-orbit position and analyzing the next 36 hours of the Shuttle's mission; the latter includes analysis of current and any predicted vector interceptions. USSPACECOM remains constantly in contact with NASA's Field Duty Officer (FDO) at JSC. Usually, if anything comes within the Shuttle's safety ellipsoid, 2x5x2 km, the NASA FDO considers a maneuver [Ref. 35]. To date, there have been several collision avoidance maneuvers involving the STS.

Another closely related collision avoidance maneuver employed by the STS concerns the orbiter's attitude while in space. As a result of over 61 hits, more than 34 Shuttle windows have had to be replaced because of impact damage since the STS program began in 1981 [Ref. 5, p. 26]. The chart depicted in Figure 49 shows the number of orbiter window replacements expected for various attitudes. The safest attitude places the orbiter's tail toward the direction of flight and the cargo bay toward the Earth. Based on this modeling, NASA has adopted this collision 'diminishing' maneuver as policy, Shuttle Flight Rule 2-77. It states that this orientation will be used at all times unless it compromises mission objectives [Ref. 9, p. 85].

Generally, however, the major deficiency with all of these activities is the error in the tracking accuracy of current sensors. There are several limitations to the existing SSN for collision avoidance purposes. These are primarily a lack of sensor accuracy and sensitivity. Current tracking capabilities are not sufficient to permit a collision avoidance maneuver to be made. In order to overcome these deficiencies, a major redesign of all SSN sensors would be required (as mentioned earlier). Theoretically, a viable collision avoidance system would have to manage several tasks as depicted in Figure 50. Currently, this is not available.

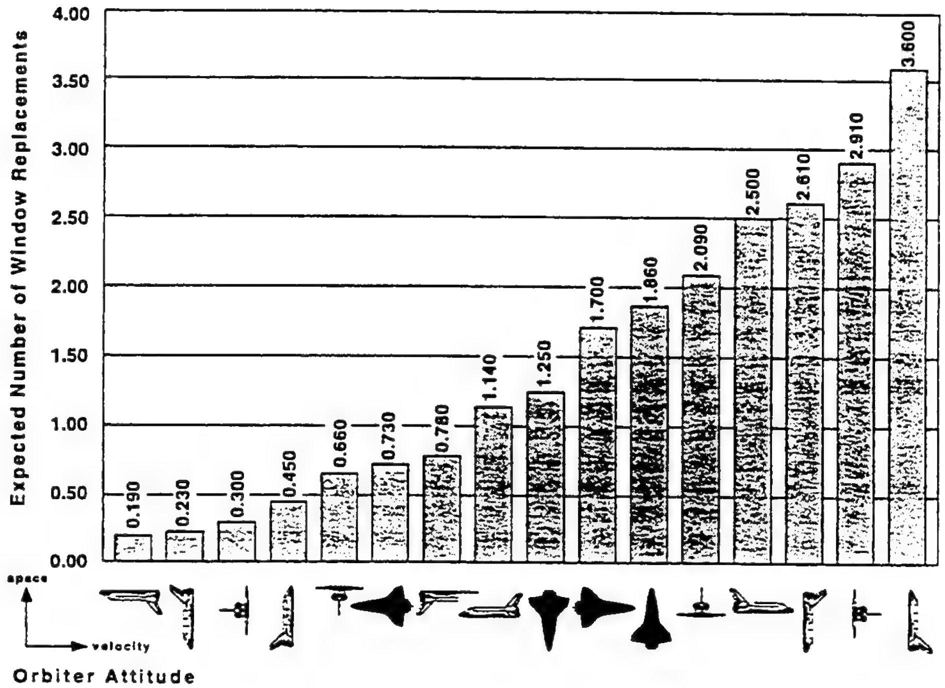


Figure 49. Shuttle Altitude Positioning Effects Rates of Window Replacements. [Ref. 9, p. 85]

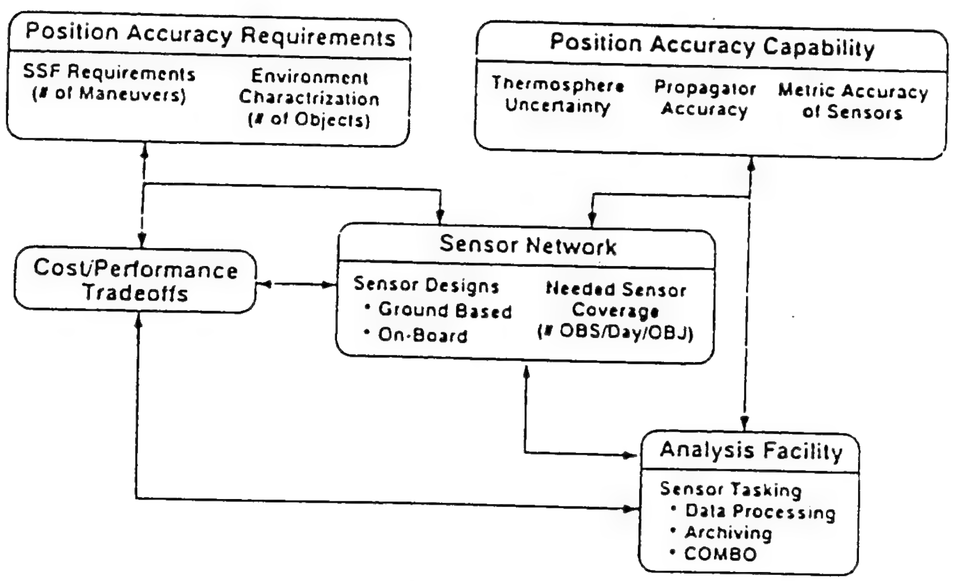


Figure 50. Task to be Executed by an Ideal Collision Avoidance System. [Ref. 30, p. 1]

There have been, however, other options discussed in order to overcome these current shortcomings. Proponents claim that it is feasible to do collision avoidance of 1cm threat objects and to do so at a relatively small fraction of the cost of the actual value of assets at risk. The first obvious recommendation is to acquire newer, more sophisticated sensors and associated data management systems. Almost immediately, this idea would be refused because of cost effectiveness considerations. However, one proposal claims that this aspect could be overcome. Clearly, it is not cost effective for the space station as a single customer. However, cost could be defrayed by providing 'service' to more than one customer. The issue then becomes whether such a new system is of value to all those who have assets at risk. This proposal calls for a series of six sensors and data management systems. It includes two existing sensor assets: an X-band version of the current NAVSPACECOM VHF system and the use of an US Army radar, the GBR-T. In addition to these two sensors, four other sensors would be required to meet a criterion that any object be tracked by a sensor within two revolutions of a predicted conjunction [Ref. 2].

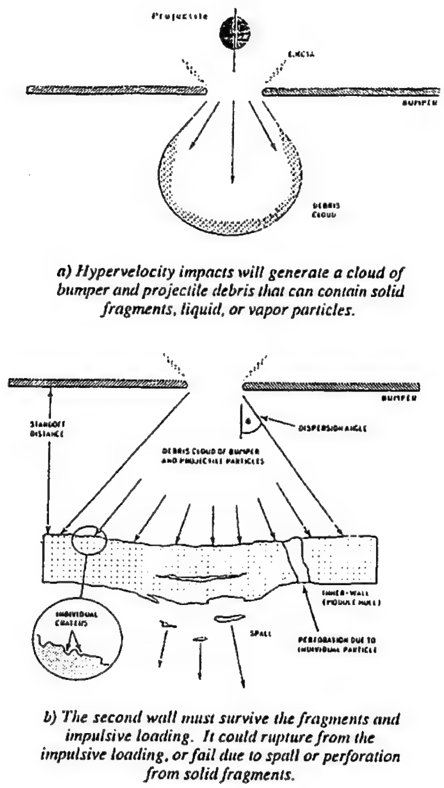
Also, collision avoidance could be enhanced through the use of on-board detection systems. On-board detection systems can sense and respond to debris too small to be tracked by current sensors. Unfortunately, there are inherent limitations to this proposal. This includes constraints associated with the on-board sensor's field of view. That is, the sensor has been shown to be able to detect possible collisions with other objects several revolutions ahead of the predicted impact intersection in the same plane; given this scenario, D. Rex from Germany's Technical University of Braunschweig, has demonstrated that the avoiding maneuver itself could be performed with less than a 1m/s velocity increment [Ref. 12, p. 65]. However, such a sensor would not be able to do so for out-of-plane threats; all threats to a spacecraft are basically out-of-plane. There would not be sufficient time for maneuver given the relative velocities involved. Moreover, a radar required in order to detect debris in all directions around a spacecraft would require too much power; clearly, this is not a viable option [Ref. 2, p. 37].

Despite these shortcomings, the necessity of avoiding maneuvers is a given due to the fact that not all the impacts of objects endangering a space structure can be made ineffective by shielding. Overcoming these difficult problems will necessitate future studies and development.

2. Shielding

Through various configurations and use of new age materials, shielding of spacecraft is now possible from debris objects of 1cm in diameter. Currently, there are four major types of shielding available to spacecraft. These are the conventional Whipple shield, the Nextel Multi-Shock (MS) shield, the Mesh Double-Bumper (MDB) shield and the Russian use of standoff screens.

The conventional approach to protect from hypervelocity particle impacts is to use two walls separated by a space, called the standoff space, in order to reduce shielding weight from that required by a single, monolithic wall. As shown in Figure 51, the function of the first sheet or 'bumper' is to break up the incoming projectile into a cloud of material containing both projectile and bumper debris. This cloud expands while moving across the standoff, resulting in the impactor momentum being distributed over a wider area on the rear wall. The back sheet must then be thick enough to withstand the blast loading from the debris cloud and any solid fragments which remain in the cloud. In the design of protective shields, a key factor governing the performance of spaced shields is the state of the debris cloud projected from the bumper toward the back plate; the contents of the 'ejecta' determines the amount of damage caused to the rear wall. The more vaporized the contents of the ejecta are the less damage that occurs to the rear wall. Hence, a penetrating particle is broken up and partially vaporized before striking the back plate (or spacecraft hull) [Ref. 36, p. 2].



a) Hypervelocity impacts will generate a cloud of bumper and projectile debris that can contain solid fragments, liquid, or vapor particles.

b) The second wall must survive the fragments and impulsive loading. It could rupture from the impulsive loading, or fail due to spall or perforation from solid fragments.

Figure 51. Dynamics of a Hypervelocity Impact. [Ref. 36, p. 2]

This arrangement, shown in Figure 52, is known as a Whipple shield. The design is named after the astronomer Fred Whipple, who first proposed it as protection against natural meteoroids in 1947. For most conditions, a Whipple shield results in a significant weight reduction over a single plate of solid aluminum. It has been demonstrated at JSC that a single aluminum sheet will be over 5 times heavier than an aluminum dual wall structure for an encounter with an aluminum projectile at 7km/s. However, Whipple shields are less effective at low impact velocities and at certain oblique angles. At these conditions, low impact pressures are generated in the projectile and bumper that results in solid fragments impacting with the rear wall. These solid parts within the debris cloud damage the rear wall significantly; vaporization of these solid elements in the cloud occurs only at higher velocity impacts [Ref. 36, p. 4].

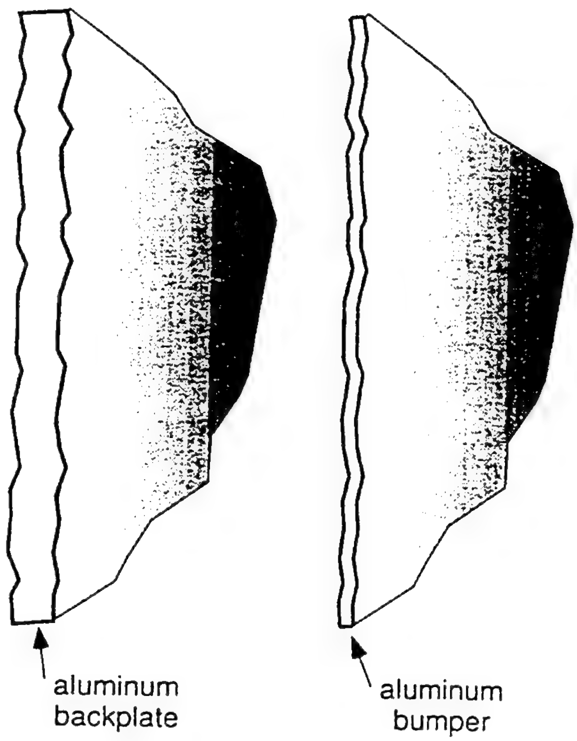


Figure 52. Whipple Shield. [Ref. 9, p. 16]

A new shielding concept under development by NASA is the MS shield. This shield, illustrated in Figure 53, consists of ultra-thin spaced bumper elements that repeatedly shock an impacting projectile. Through multiple shocking of the projectile, the projectile's thermal state is driven to a higher condition than that achieved by a single shock provided by a Whipple shield. In fact, the extent of projectile melting and vaporization that would be expected at 10 km/sec for a Whipple shield is achieved by the MS shield at 6.3 km/sec. Hence, the MS shield overcomes the low velocity vulnerability characteristics of the Whipple shield. Also, a 30 to 40% reduction in shielding weight, compared to the conventional aluminum Whipple shield, is possible using the MS shield concept [Ref. 36].

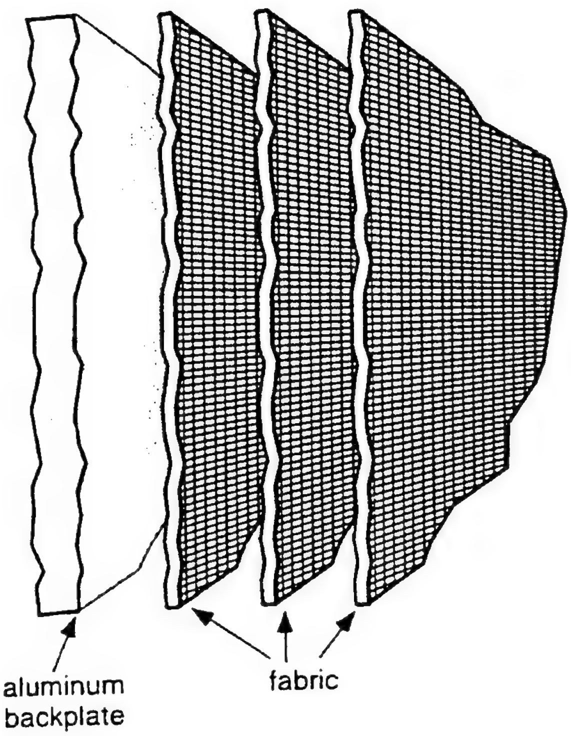


Figure 53. Multi-Shock Shield. [Ref. 9, p. 16]

The MDB is another advanced shield that provides similar protection and weight savings benefits as the MS shield. Figure 54 illustrates a schematic of the shield. It was developed to show that major improvements in shielding protection could be achieved over conventional Whipple shields by simply adding a mesh a short distance in front of the existing Whipple bumper and putting a high strength fabric layer in the standoff area. Tests have shown that a double bumper system with a mesh outer bumper exhibits superior performance than the same weight double bumper consisting of two continuous aluminum sheets. The aluminum mesh does not produce damaging secondary ejecta particles that are created in conventional Whipple aluminum bumper impacts.

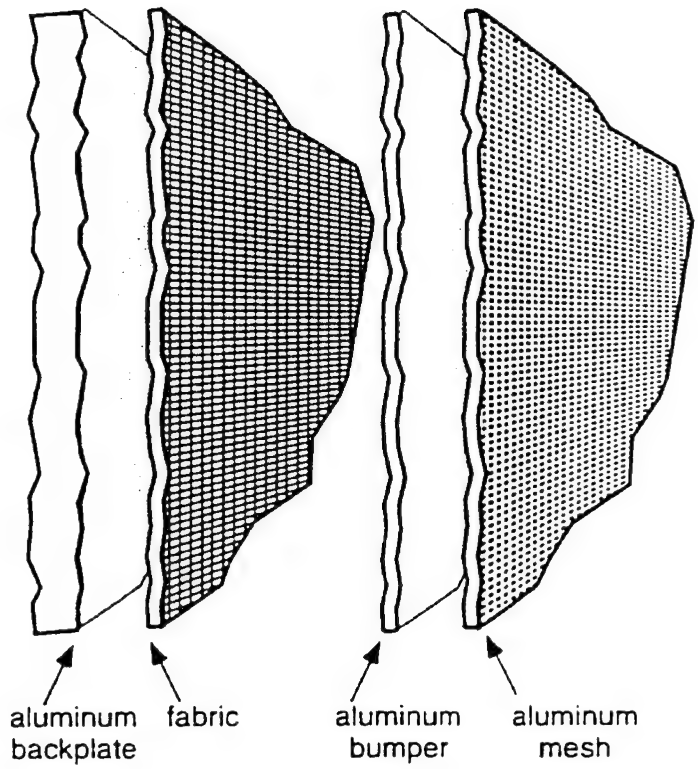


Figure 54. Mesh Double Bumper Shield. [Ref. 9, p. 70]

In addition to the shield concepts discussed above, Russian spacecraft designers employ the use of a Whipple type shield concept termed standoff screens. Unlike the other techniques described above, standoff screens are an informal manner of providing some degree of shielding to spacecraft; optimization of shield design and associated weight is not present in this type of shielding. In a study conduct by Kaman Sciences Corp. for NASA on the Mir Space station shielding, Dr. McKnight concluded that the Russians do not have a standard shield design per se. Instead, they rely on an aluminum bumper about 2 cm from the spacecraft's pressure wall; the screen is about 1mm in thickness. This sheet has been described as just thick enough to vaporize the impactor [Ref. 37, p. 9].

In order to maximize a shield design, a simplified method has been used to roughly size the thickness of the bumper(s) and the rear wall of meteoroid/debris shields and estimate shielding weights. This method is illustrated in Figure 55. Although adequate for deriving estimates of shielding weights and for performing quick trade studies, this approach is not suitable for verifying design adequacy or for assessing design options to greater level of detail because of the overly simplified assumptions on meteoroids/debris impact angle and velocity distributions.

In summary, shielding techniques are now available that provide adequate protection against debris particles of 1cm, or slightly larger, in diameter. Maximizing a shield's protective properties involves an interplay between plate thickness, plate spacing and material weight. A renewed emphasis on the development of low-weight shielding alternatives to the conventional Whipple shield concept have been required as a result of the growing threat from orbital debris.

1. Given space vehicle size, orientation, orbital altitude (h), inclination (i), and years of exposure

2. Select desired meteoroid and debris protection capability, such as probability of no-penetration (PNP), over a specific time period (t).

3. Calculate effective exposed surface area (A) for each side of oriented space vehicle or for entire surface of randomly oriented space vehicle. Include effects of shadowing from adjacent structures. Include flux factors on each surface of oriented space vehicle. Include Earth shadowing and focusing factors for meteoroids.

$$A = f(\text{size, orientation, altitude, M\&D directionality})$$

4. Calculate meteoroid and debris penetration flux, $F_{M\&D}$.

$$F_{M\&D} = f(PNP, A, t)$$

5. Calculate particle diameters, d_M & d_D, of meteoroids and debris that the space vehicle must be protected against to meet required protection level.

$$d_M \;\&\; d_D = f(F_{M\&D}, h, i, \text{Solar flux})$$

6. Select shield type: monolithic, 2-sheet Whipple shield, Multi-Shock shield, Mesh Double-Bumper shield, etc.

7. Calculate shield parameters: bumper and rear wall thicknesses, spacings, and weights. These are a function of shield type and shielding material properties; and meteoroid/debris particle size, velocity, density, shape, and impact angle.

Figure 55. Shielding Methodolgy. [Ref. 38, p. 2]

C. SUMMARY

In closing for this chapter, we have explored most aspects of current and proposed space debris minimization and active debris protective measures. With this in mind, a present desideratum would be to pursue those activities and practices that are most likely to lead to a stable and desirable environment over the long term while addressing current day survivability threats. More so, since the continued use of the LEO environment appears likely, and with it the level of activity involving NASA's Civil Needs Data Base. The need for orbital design considerations is clear. One manner for effectively achieving this goal is the topic of the final chapter. Finally, one last comment. By the now, the reader may have come to the realization that there exists a great inconsistency in terms of shielding and tracking capabilities. That is, given the limitations of current tracking capabilities and of available shielding techniques, a 'gap' in protective measures is evident. This gap and its effects are highlighted in Figure 56. As frightening as this realization may be, it simply serves to reinforce the fact that orbital debris is a tremendous problem whose solution will require unprecedented efforts by all concerned.

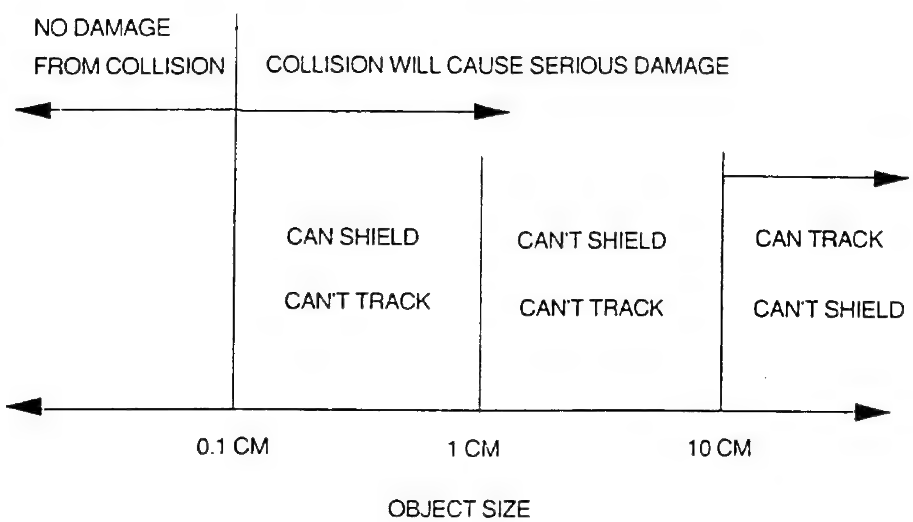


Figure 56. The Bottom Line. [Ref. 39]

V. CONCLUSIONS AND RECOMMENDATIONS

A. WHERE ARE WE?

Thus far, several interesting issues have come to light. The debris issue has been examined and analyzed in terms of its physical and behavioral characteristics, and its current status in the international arena has also been explored. The dynamic nature and relationship of several of the discussed properties are summarized in Figure 57, where the various sources of orbital debris are delineated. The feasibility of several debris-related techniques for addressing the situation have been discussed as well. A synopsis of the advantages and disadvantages to each major debris abatement technique is presented in Figure 58, where "operational debris" refers to operational satellites as cataloged by USSPACECOM. It must be noted that the column labeled technical feasibility is intended to indicate the level of difficulty of a particular technique as compared to other techniques. This is because, as previously noted, *no* avoidance measure can be characterized as "simple," in part due to the fact that current ephemeris are not accurate enough to avoid debris on a regular basis. As has been demonstrated, more data, and more sensors, are necessary to avoid collisions with space objects.

The research effort has reached its principal goal of shedding light on the orbital debris dilemma by examining and analyzing the current extent of the debris problem, uncovering a variety of truths and fallacies along the way. In this final chapter, general observations on the subject are made and possible solutions are proposed, based upon the information presented thus far.

The facts of the case point to and support several undeniable observations concerning the debris issue. These indicators paint an unsettling portrait. The biggest concern associated with the debris issue is that it is not a static problem; to the contrary, it is very dynamic and complex by nature. It is a physical and threatening problem that is

constantly growing and worsening in effect with time. None of the efforts currently under way have demonstrated the ability to temper the rate of this growth, as is evidenced by the information presented in Chapter II of this paper. The dangers of the orbital debris environment threaten the very future of space flight activity.

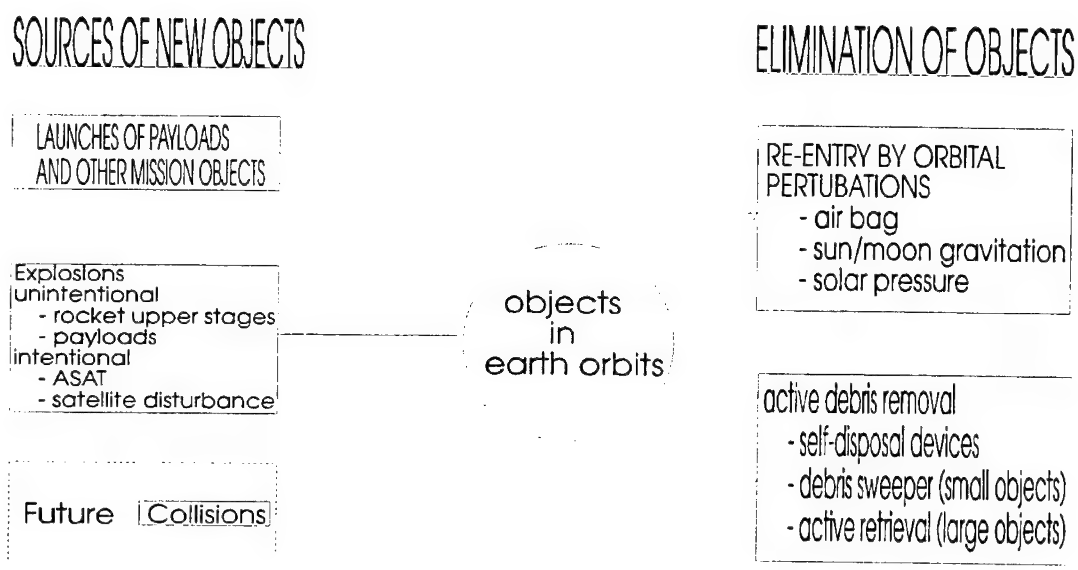


Figure 57. Debris Population Dynamics. [Ref. 17]

mitigation measure			short/mid term effect	avoidance of cascading	technical feasibility	costs
preventive	small	prevention of P/L and R/B explosions	+	–	R/B simple P/L moderate	low to moderate
preventive	small	avoidance of operational debris	+	–	simple	low to moderate
preventive	large	de-orbit of P/L and R/B after mission	–	+	simple to moderate	high
subsequent	small	LASER, foam balls large foils	+	–	very difficult	very high
subsequent	large	active removal e.g. TERESA	–	+	very difficult	very high

increase of mission costs: low < 2% moderate < 5% high 5 to 15% very high > 10^9 $

Figure 58. Efficiency, Feasibility and Costs of Debris Mitigation Measures. [Ref. 17]

Another realization has been that there is no guiding policy of substance on debris. Coupled with this is the fact that there doesn't seem to be a sense of urgency involved about the problem. While there is general acknowledgement that the problem exists, there is hesitation in developing a comprehensive plan for solving the problem on an international level. The fact that isolated efforts have been made to decrease the growth of the orbital debris population is aggravated by this lack of international consensus, because it takes so much time for the effects of mitigation efforts to become apparent.

The author believes this is primarily due to either decision-makers, policy makers, or governments that haven't come to grips with the fact that it is a threatening problem and that coping with this problem is going to take a lot of effort in terms of money and resources.

B. UNDERLYING INDICATORS

1. Observations

The first point to be made is that the lack of leadership in dealing with the orbital debris issue is at the heart of the problem. Individual agency efforts around the world demonstrate that there is interest in the space program community about addressing this problem, but the lack of a participant willing to take on leadership responsibility is enough to keep those efforts confined to an ineffective role. Beyond solution generating shortcomings, however, the very lack of leadership on the issue is itself exacerbating the lack of awareness about its severity. With no one willing to champion the cause, it is unlikely that "orbital debris" will ever arouse much interest or action in the democratic populations that financially maintain space programs.

Secondly, it must be noted that the current level of organization and action on the problem is insufficient to the task. This is so because of the lack of centralized standards, monitoring, and control. While NASA is, after all, the *national* space organization, NASA and DoD both contribute to the US share of the space exploration and use market, and there is no mechanism nor protocol to jointly address the orbital debris issue. Beyond the lack of a single vision on the national scene, however, is DoD's lack of coordinated effort. There is no single entity through which to coordinate the activities of the various DoD departments who are involved in space programs.

This lack of coordination and control is magnified at the international level, and the growing list of participants in orbital space activity presents yet another dimension to a problem that is already projected to grow critical in the near future. The complexity of the problem is further compounded by the fact that it is moving beyond the interaction of national governments and into the private sector, where Motorola Corporation is engaged in employing an exclusive communications satellite network. One could easily imagine that each of the companies today engaged in installing and maintaining communications lines will one day expect the right to establish orbital communications equipment as a matter of course. The orbital debris issue, therefore, will require the kind of uniform

standards and efforts that can only come from universal acceptance. If the processes involved in reaching and maintaining international agreements are not soon begun, it is very doubtful that a solution will be possible prior to the development of a critical situation in near-Earth space. Viewed in this light, all of the various program and/or agency level activity regarding orbital debris does nothing to mitigate the size of the problem to be faced over the horizon.

This leads to yet another observation: when agencies and/or individual programs examine orbital debris issues, it is in the very specific context of what that agency or program is trying to accomplish. In other words, the efforts of, for instance, the European Space Agency to deal with orbital debris concerns in relation to an upcoming satellite deployment program says nothing at all about dealing with the orbital debris problem as a whole. This makes the point again: only a total solution will guarantee future freedom from concern about the threats posed by orbital debris. As has been noted in previous chapters, discussions related to measurement formulae, modeling technique, shielding methodologies, and other factors leave unaddressed the kind of comprehensive approach that would be evidenced, for instance, by the establishment of specific guidelines to be followed by everyone engaged in the design of spacecraft.

By the same token, however, the tendency to curb "over-study" of the issue must be avoided. While action is needed, there remains a great deal of information to be gathered in order to maintain adequate safeguards. Between the beginning and end of negotiations to agree on universal action, in fact, information will come to light that substantially influences the content of such agreements.

When one looks at the effectivesnesss of existing debris mitigation practices, they are found to be wanting. Efforts to mitigate the problem are limited in scope and inadequate in terms of results. This is so because, in the case of already designed spacecraft, mitigation cannot redesign the vehicle to achieve goals; in the case of spacecraft currently being designed, mitigation efforts are rarely employed. In the first instance, the best case scenario is to make a minimal reduction in the amount of debris

placed into orbit. In the instance of spacecraft in design, other pressures have combined to force debris mitigation off of the drawing board.

Most significant among these pressures are those related to budget issues. Debris mitigation-incurred budget line items are perceived as unnecessary expenses. At worst, debris mitigation forces a design team to include budget items that are brought about by consideration of current and future spacecraft *survivability* issues, which does nothing to endear a budget director or Congressman to a particular program. This is another area in which the lack of leadership-generated public awareness of the orbital debris dilemma often serves to offer up debris mitigation funding on the altar of budgetary reduction. The very wording of the 1988 National Space Policy reinforces the idea that debris mitigation is, unwisely, given a back seat to other considerations, by saying, "reduce the accumulation of space debris consistent with ... cost effectiveness." In fact, the first ever spacecraft to be designed with orbital debris considerations is the yet to be deployed Space Station.

This is not to say that spacecraft designers and builders do not conduct vulnerability and risk analysis for their projects. Once it is determined that debris is within an acceptable level of risk, with low Probability of No Penetration (PNP), however, they move on to the rest of the design process. What is needed is a proactive effort toward debris mitigation.

C. NEW CONCEPTS

1. Change of View

In the course of this endeavor, it has become apparent that the debris issue is a complex one. Existing efforts address it by breaking it apart into smaller, more manageable pieces. This apparently makes complex tasks and subjects more manageable, but really serves to disassociate related elements of the same overall problem. In this state of fragmentation, the consequences of our actions are unclear. When trying to affect the big picture, the pieces must be put back together. But, as physicist David Bohm says,

the task is futile - it is similar to trying to reassemble the fragments of a broken mirror to see a true reflection. [Ref. 18, p. 68]

It is the purpose of this section to put forward the idea that the issue of space debris must be viewed under a different light, a shift in perspective. The intent is not to develop a solution and present a means for its implementation, which is beyond the scope of this work. Rather, it is the intent to illustrate that the current state of the debris issue, like so many other complex problems challenging our world, is complicated by the inability to see it as a whole.

a. Systems Thinking

Systems thinking is a discipline for seeing wholes. It is a framework for seeing interrelationships rather than things, for seeing patterns of change rather than static snapshots. It is a set of general principles spanning fields as diverse as the physical and social sciences, engineering and management. It is also a set of specific tools and techniques, originating in two threads: in "feedback" concepts of cybernetics and in "servo-mechanism" engineering theory dating back to the 19th century.

Systems thinking is needed to address the orbital debris issue in order to avoid becoming overwhelmed by complexity. The scale of this complexity is without precedent. All around us are examples of systemic breakdowns - problems such as global warming, ozone depletion, the international drug trade and the US trade and budget deficits - problems that have no simple local cause. Systems thinking is a discipline for seeing the "structures" that underlie complex situations, and for discerning high from low leverage change. That is, by seeing wholes we learn how to foster system "health."

In our efforts to address circular relationships, it is human nature to try to resolve those circles into straight lines. Herein lie the beginnings of our limitations as systems thinkers. In order to become successful in systems thinking, the linear viewpoint must be abandoned in order to realize that the world around us is organized in a circle or loop of cause-effect relationships which are called feedback processes. Note that in systems thinking, feedback means any reciprocal flow of influence; nothing is ever

influenced in just one direction. And, most importantly, from the systems perspective, the human actor is part of the feedback process, not standing apart from it. This represents a profound shift in awareness, allowing systems thinkers to realize how they constantly influence, and are influenced by, systems.

Systems thinking applies to the orbital debris issue due to its fundamentally dynamic complexity. There are two types of complexity: detail and dynamic. Conventional forecasting, planning and analysis methods are equipped to deal with detail complexity; they cannot, however, handle dynamic complexity which involves situations where cause and effect are subtle, and where the effects over time of interventions are not obvious. Such is the case with the orbital debris situation. When the same action has dramatically different effects in the short run and the long, there is dynamic complexity. When an action has one set of consequences locally and a very different set of consequences in another part of the system, there is dynamic complexity. And, when obvious interventions produce non-obvious consequences, there is dynamic complexity. Systems thinking is ideally accomplished over the long term, and for all these reasons space debris ties in closely to the notion of systems thinking.

Since the debris situation is fundamentally a problem of dynamic complexity, systems thinking can offer new insights into the causes and possible cures. Addressing the orbital debris issue requires seeing the interrelationships, the delays between action and consequence, and the patterns of change, not just the 'snapshots' of the problem. Seeing the major interrelationships underlying a problem leads to new insight into what might be done to solve it.

b. Shared Vision

Another application that the space debris problem may benefit from is the development of what social scientists call a shared vision. A shared vision is beyond an idea; beyond even an *important* idea. It is, rather, a driving force of impressive power. It may be inspired by an idea, but once it gets started then it is no longer an abstraction. It is palpable. People begin to see it as if it exists. Few, if any, forces in human affairs are

as powerful as shared vision. At its simplest level, a shared vision is the answer to the question "what do we want to create?" In learning organizations, shared vision is vital because it provides the focus and energy for learning. [Ref. 18, p. 205]

Shared vision matters because it establishes an overarching goal. A shared vision also provides a rudder to keep the learning process on course when stresses develop. With a shared vision, one is more likely to expose his ways of thinking, give up deeply held views as they are proven invalid, and recognize personal and organizational shortcomings. All troubles seem trivial compared with the importance of what one is trying to create. Also, shared vision fosters risk taking and experimentation. Lastly, shared vision enables a commitment to the long term view. Again, given the current state of 'vision' within the space community, the debris issue can stand to gain much from the development of an international sense of shared vision.

Shared vision is essential to developing an approach to the problem of orbital debris because, given the lack of an international body of law, it is a means to an end. Visions spread because of a reinforcing process of increasing clarity, enthusiasm, communication and commitment. As people talk, the vision grows clearer. As it gets clearer, enthusiasm for its benefits builds. Where international policy fails, shared vision can drive people to doing the right thing in terms of space debris efforts until it can be repaired.

2. New Methodologies

This section deals with less ethereal suggestions, ideas firmly planted in scientific procedures. They encompass thoughts regarding new guidelines for designing spacecraft. The underlying concept is that spacecraft must be designed in such a manner that the environment, in our case orbital debris, is the design driver.

a. The Obvious

After reviewing all the available data concerning the subject, proactive debris mitigation efforts appear to be the only method by which to insure that there is no future exacerbation of the problem; if no new sources of debris are injected into LEO, and given

sufficient time, argues Kessler, the problem will correct itself through natural means (orbital decay). In this section, mitigation applications refer to those presented earlier on in Chapter IV; they include both design and operational procedure considerations.

The importance of the group of activities labeled as mitigation practices cannot be overemphasized. Utilization of these practices in different application scenarios can contribute significantly to the defeat of the debris problem. For the most part, two general scenarios exist. The first involves those payloads and launch vehicles already near completion or constructed, and second includes those space vehicles and satellites in the design phase and/or coming in the future. Different mitigation applications can be applied in both these cases to help contribute to the reduction and future creation of orbital debris.

Mitigation applications are more difficult in the case of existing spacecraft and vehicles. This is true both in terms of technical application and cost effectiveness. Mitigation practices in this case would normally consist of after the fact design alterations or device add-ons, or changes to current launch procedures and practices and on-orbit operations, e.g., de-orbit before fuel is depleted. Designing after the fact always creates a myriad of unknown problems which for the most part are strenuous and time consuming to overcome. A secondary fallout from this condition is that additional time and resources usually contribute to additional moneys being spent on the project, a prospect not too pleasing to any project manager. Moreover, at this point and time in the development process, few projects are within their projected fiscal boundaries. Introduction of any type of design change at this point would be unappreciated and unlikely to be accepted. Hence, in this case, it would be difficult to introduce mitigation practices and convince managers of the intangible benefits regarding debris minimization.

If mitigation cases are properly introduced at the onset of a space project, however, the probability of survival of these applications is much higher. At this stage, vehicles are designed around the debris environment, technical obstacles are addressed early on and cost is minimized.

In addition to early application of these activities, a sincere commitment to the principles of surrounding mitigation/reduction activities must be developed. Debris mitigation must be a part of the operations concept that accompanies the basic statement of need or program initiating document. Debris mitigation must be a clearly stated policy in the concept definition phase. In essence, decision makers must make a commitment to ensure debris mitigation is a priority throughout the various phases of a space vehicle's lifecycle. [Ref. 2, p. 571] Without a commitment, or as Dr. Senge would say, a 'shared vision', mitigation applications cannot overcome the real enemy: money. Failure to achieve either one of these requirements, early application and a commitment to the ideal, will diminish the possibility of any type of mitigation measures being accepted into a space project.

The mitigation practices must be looked at in systemic terms; that is, a closed loop where each stage influences the next. Refer to Figure 59. Borrowing from the concepts of Dr. Senge, the use of mitigation applications must be viewed in terms of a closed system or cycle. Viewing the debris situation and the application of mitigation practices under this light may offer new perspectives and insights into the debris problem. Instead of looking at pieces of the puzzles, seeing the whole picture can help one to overcome the mental structures which prohibit one from seeing how the parts affect the whole. Although detailed discussion of this approach is beyond the scope of this thesis, the introduction and application of this idea is not.

Thus, despite budgetary forces, mitigation applications must prevail. Unfortunately, there is no given formula to apply in order to assure the survival of mitigation practices within a space-related project. It really comes down to ethereal concepts such as doing what is right and assuming a responsible posture.

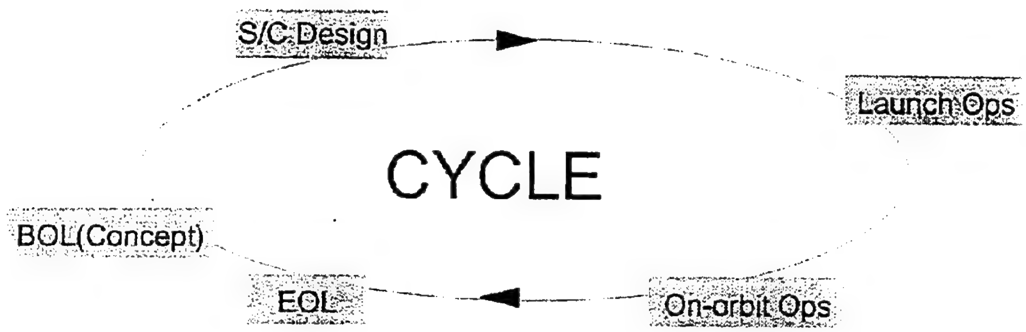


Figure 59. Debris Mitigation Cycle for Spacecraft.

b. Available Tools

In the course of this effort, several valid tools for the applications of debris related methods were discovered. Similar to most debris actions, it was found that these analytical tools were not being used as much as they should be in light of the threat that debris poses. This section highlights three major tools encountered and discusses their applicability to the debris situation. These are the Bumper II program from JSC, the EnviroNET on-line/interactive service from Marshall Space Flight Center, and the use of vulnerability and risk assessment analysis methods. These "tools" can be used to bring about some of the applications discussed thus far concerning the incorporation of mitigation measures. Again, the scope of this thesis limits itself to discussion of and application of these important tools to the design of space vehicles.

(1) Bumper. Bumper is a computer program used at JSC to evaluate Micrometeoroid and Debris (M&D) damage and shield penetration risks. It links the M&D environments with results of Hypervelocity Impact (HVI) tests and analysis and element geometry to calculate impact risks. [Ref. 40, p. 6] Originally developed by Boeing, Bumper has been modified by NASA to incorporate updated shield response equations; additionally, Bumper predictions have been correlated with the known history

of M&D impacts observed on LDEF. Among its many uses, Bumper is used in analyses of spacecraft shielding systems in order to identify M&D risk drivers. The object of these analyses is to optimize shielding weights, thereby saving weight and /or improving M&D survivability, by distributing the weights on a particular element to more equally balance M&D penetration risks with shielding weight. In addition to assessing the validity of shielding proposals, the use of Bumper also allows the user to see what effect the 'shadowing' and the effect of orientation has on the M&D penetration risks. Shadowing refers to the use of non-critical components to cover or shadow more critical components, thereby acting as a shield against incoming debris. Orientation deals with the flight attitude of a vehicle; as was alluded to with the STS, lower probability of penetrations occur at specific attitudes and minimizes M&D risks. In all, Bumper is a M&D damage assessment technique which can be used effectively, as with the Space Station, for impact probability analyses of any space vehicle.

(2) EnviroNET. EnviroNET serves a similar purpose in that it helps to define the debris environment and, thus, design for it accordingly. This is a NASA service facility that can provide spacecraft designers with on-line or dial-up technical information on space environmental conditions. Included in the system is an interactive graphics facility to model debris collisions likely to be encountered by spacecraft in a variety of orbital regimes. The main EnviroNET topical areas to space debris are found in section 8.8.2 of the handbook. [Ref. 41, p. 18]

In all there are five interactive models dealing specifically with the orbital debris topic. These include an orbital debris model, a meteoroid model, an orbital decay model, a solar flux data model and a probability of impact model. Through the use and incorporation of the results of these models, spacecraft or payload design can be assessed against the most severe combination of natural and artificial environments.

(3) Vulnerability and Risk Analyses. Lastly, there is the use of certain design analyses procedures to help identify spacecraft vulnerabilities and potential hazards, specifically, the use of vulnerability and risk analyses. It is not known with certainty

whether these procedures are used in the design of a spacecraft or to what extent they are incorporated into the overall design process. Specifically, spacecraft design must include a process by which threats to a spacecraft are identified. Once identified, appropriate measures should then be incorporated into the design of the vehicle in order to defeat or overcome these hazards. This is the goal of a vulnerability type analysis. A summary of tasks for designing a less vulnerable spacecraft may include those tasks identified in Figure 60. Through the use of similar processes, vulnerability reduction to spacecraft from debris can be institutionalized into the overall design scheme. The designer can also improve spacecraft vulnerability by being aware of and by using other methods to reduce a spacecraft's susceptibility to various threats. To skillfully approach the improvement of a space vehicle's ability to survive in its hazardous operational environment, a responsible designer must artfully blend together and utilize concepts from both the vulnerability and susceptibility reduction principles.

As for risk analysis techniques, the general concept remains the same. That is, to identify, characterize, quantify and evaluate potential hazards to a spacecraft. To a certain extent, both analysis types overlap one another and provide the same information for design considerations. In principle, both describe the threat and address methods for coping with the same. In terms of debris, the use of any one of these procedures in the design methodology of a spacecraft would benefit the cause for either debris mitigation or protective measures because the true extent of the debris threat would be brought to light.

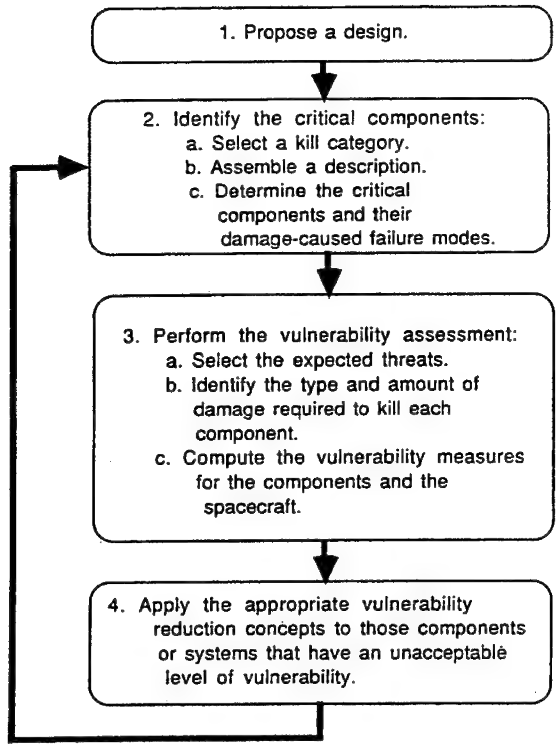


Figure 60. Summary of Tasks the Vulnerability Analysis. [Ref. 42, p. 114]

(4) Summary. The importance of these tools is self-evident. Through the use of these tools, or many such like items, risk assessment of the debris environment can be properly executed. Firstly, identify the hazards and risks that are inherent to the system. Next, calculate their causes and probabilities for various designs. Lastly, decide which risks can be accepted. In this manner, separation of risks arising from the operation of equipment from those resulting directly from the effects of the space environment can be accomplished.

c. Design Flow

In an informal survey of five different space projects, from both DoD and civilian organizations, it was discovered that debris mitigation practices were seldom used in the design of a space vehicle or satellite. As previously mentioned, orbital debris

considerations into the design of a space vehicle usually consist of a quick check into the probability of collision with the same. Usually, based on their calculations, the probability of collision is very remote and, consequently, dismissed as insignificant or as not being a factor. In the survey, this attitude seemed to be the norm. Moreover, when specifically asked, organization representatives stated that debris mitigation steps were not formally incorporated into the design process of their vehicles.

The only exceptions to this rule were the three spacecraft mentioned earlier in this paper: the Space Station, IRIDIUM and RADARSAT. Their design methodologies heavily incorporated the application of debris mitigation practices, as well as active debris protection application. IRIDIUM is the first of its kind to implement a cost and technically effective debris mitigation plan. In a telephone interview, Mr. Robert Penney, of Motorola SATCOM, verified that cost effectiveness studies for IRIDIUM showed no marked increase in cost for the incorporation of debris mitigation practices in the design and operational phases of their spacecraft. Their key to success, as stated by Mr. Penny, was a commitment to debris mitigation in the very first phases of programs. Though Mr. Penny did not provide a specific reason for prior incorporations of mitigation programs, he said it probably had more to do with the survivability issue than with the pursuit of a mitigation of orbital debris policy. Similarly, the RADARSAT team assessed the hazard of the space debris environment and incorporated protective measures into the design of their spacecraft. Through the analysis of the space debris threat and various associated test programs, primarily in the HVI facility at JSC, their findings led to a number of design modifications. Unfortunately, in their case, the spacecraft design was already well advanced when it was determined that debris protective measures were necessary. In the future, most, if not all, spacecraft will have to be designed in a similar manner in order to overcome the debris environment of their day.

In order to quantify the threat of orbital debris, spacecraft designers must undertake an analysis of the orbital debris environment specific to a spacecraft's orbit, and an analysis of the spacecraft's vulnerability to that environment. In this context, debris

mitigation and protective measures are applicable. Again, it is not the intent of the author to elaborately describe a design methodology, but rather to discuss general principles associated with spacecraft design methodologies.

The proposal is simple. First, all future spacecraft designs should include a deep commitment to the principles and incorporation of debris mitigation applications. Design procedures include all those methods for reducing the production of new debris sources at all phases of a satellite's lifecycle; operational procedures include those actions that allow a satellite to become less susceptible to the dangers of the debris environment through the manipulation of orbital parameters and deployment procedures. Secondly, that active debris protective measures, such as shielding or collision avoidance systems, be incorporated into the design of a space craft only after conducting detailed vulnerability and risk assessment analyses. The key to this proposal is, of course, early initiation of these concepts in the design cycle of a space vehicle. As we have seen, to implement a cost and technically effective debris mitigation plan, space operators must commit to debris mitigation in the very first phases of a space program. It must be a clearly stated policy that maintains prominence in the systems engineering and trade-off analysis phase. Most importantly, it must be a matter of resolve in the operational phase. The entire gamut of mitigation applications cannot be applied to every spacecraft; however, if at least one major application is considered, then the future may not be as bleak as we may think.

D. IMPLEMENTATION

Specific plan steps to deal with the orbital debris problem are beyond the scope of the current work. In general terms, however, an intent and direction for action can be described.

Space organizations are inherently bureaucratic, and this presents the most fundamental problem to implementing debris mitigation efforts on a comprehensive scale. Innovation must be present in any organization that intends to capitalize on new strategies

intended to bring about a shared vision. Organizations will resist these kinds of changes at every level, and this is because of what has been termed the "bureacratic mindset", which seeks comfort in the established and is unsettled at the thought of change.

Fundamental change is necessary, however. The only way for the various US and other national and international space programs to establish processes for addressing and effectively dealing with orbital debris issues is for those organizations to address those issues at every stage of involvement. This necessitates the development of a learning organization, with parallel learning structures that allow for feed-back on critical issues.

In a learning environment, incorporation of the various tools available for mitigation efforts, such as EnviroNet and Bumper, described above, will mean incorporation of the people and concerns present in those existing activities. In this way, individuals involved in collecting and processing information on orbital debris will take an active role in the relationship with space program designers and administrators, rather than simply passing information on with little understanding of its intended use or post-use evaluation of its effectiveness.

Restructuring space programs to include the widest range of participants will establish an environment in which systems thinking can be fostered and a shared vision developed. When existing tools are employed, and new tools developed, within the context of a larger learning organization, the resulting processes lead to design flow, wherein the individual efforts and separate concerns of component projects provide feed-back for one another throughout the design and implementation process.

The difficulties present in implementing a new way of thinking in US programs pale in comparison to those associated with moving the effort to the international arena. However, no amount of improvement in US programs will result in real change without cooperation at the international level. In many ways, the learning organization that must be developed to effectively pursue space objectives for the US must grow beyond the country's borders to include organizations in other nations and regions.

Beyond the establishment of international agreements and standards, however, lies the enforcement problem. In a time when compliance with established agreements is often called into question among the closest international partners, the prospects for compliance with orbital debris mitigation agreements may appear bleak. Like the rest of the obstacles to real debris mitigation, however, this issues must be proactively addressed, and the establishment of systems thinking and shared vision will go a long way toward paving the ground for willing compliance.

E. CONCLUSION

The points made in this work have by no means been intended as an exhaustive evaluation of the space debris issue. An effort has been made, however, to maintain an unbiased perspective from which to draw basic conclusions regarding a logical course of action.

The first of these conclusions, then, is that obital debris can indeed pose a significant threat to operations in space. None of the estimates of current and future debris mass presented in Chapter II fail to point toward the threat of a "critical mass", at which point space-based operations are rendered impossible. Further evidence of the significance of this problem has been apparent in the simultaneous drift of space agencies around the world toward debris mitigation strategies. Increasing numbers of scientists are voicing concern over threats from orbital debris. This movement to recognize the issue and the increasing demand for information and projections from those involved in mission planning are remarkable for the simple fact that orbital debris has yet to receive the attention of a possible major threat. There is a notable lack of leadership, specifically at the international level, in the orbital debris control arena. Control strategies, including mitigation, retrieval, and de-orbiting, are implemented on a program-by-program, agency-by-agency basis. The problem is accelerated by the entrance of additional nations in the "space club."

On the other hand, organizations representing US, European, and Japanese space agencies have undertaken programs on their own and even met together to explore the creation of an international set of standards for space exploration that will avoid the "carpet of debris" foreseen by the more pessimisstic of industry analysts. The point, simply put, is that awareness is spreading about the need to act on orbital debris in order to assure future access to orbital space. What remains to be found is the leadership to forge a concerted effort toward standards and results. Dedication to the goal is required of a responsible player in the game of space; as one person noted, "outer space is by nature and treaty a global commons, available for use by all nations. With this potential comes responsibility for keeping space safe." [Ref. 2, p. 571] Recognition of this responsibility has occurred, but the commitment to keep space safe does not exist. It is paramount to develop and foster a responsible attitude throughout this entire process; as we've seen, its a closed systemic process. With a proper approach to the entire process, the problem could be eliminated.

Beyond complimentary international goals, however, the US faces a more pressing problem. The planned Space Station will necessarily maintain an orbit that will force NASA to develop new and innovative solutions to orbital debris collision problems. Skeptics note that the Space Shuttle seems to avoid the problem well enough, and this is true, but the probability of an encounter increases with the term of exposure in the orbit and size of the satellite. If the US intends to take a lasting place in orbital space, approaches to orbital debris issues remain a basic requirement.

The primary need remains information. The ability to track existing debris must be employed in combination with a plan to control future debris to arrive at a solution. Siding with caution, given an uncertain threat, is an instinctive and precautionary move that cannot be easily dismissed or unsubstantiated. More so than anything, it seems to be common sense. If we are faced with a threat and we are not sure of the extent or degree of that threat, common sense dictates that we arm ourselves or prepare ourselves as best we can and certainly not make conditions worse than what they are.

Most importantly, there is the need to act now, before it's too late. We must intervene now while we can still can affect the outcome of the future environment; we cannot allow it to run away from us to the point where we can no longer affect or influence it.

In closing, the reader is left with a small note on things which may yet come to be. In the not-too-distant future, Earth could be exhausted of all its resources and remain an empty husk. Mankind's only chance for survival lies in the stars. Unfortunately, man is trapped on Earth because the surrounding debris belt prohibits passage to the stars.

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